Geometry Engineering in Small Systems and Collective Flow Results from PHENIX

Qiao Xu for the PHENIX Collaboration

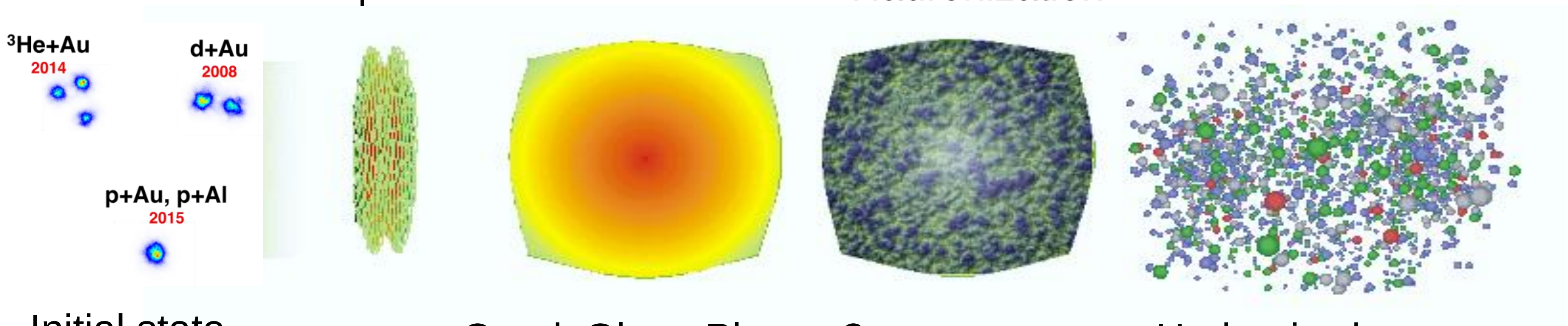
Geometry handles on collectivity in small systems

Geometry Engineering

Test if the initial geometry is translated to final-state momentum anisotropy

Pre-equilibrium

Hadronization

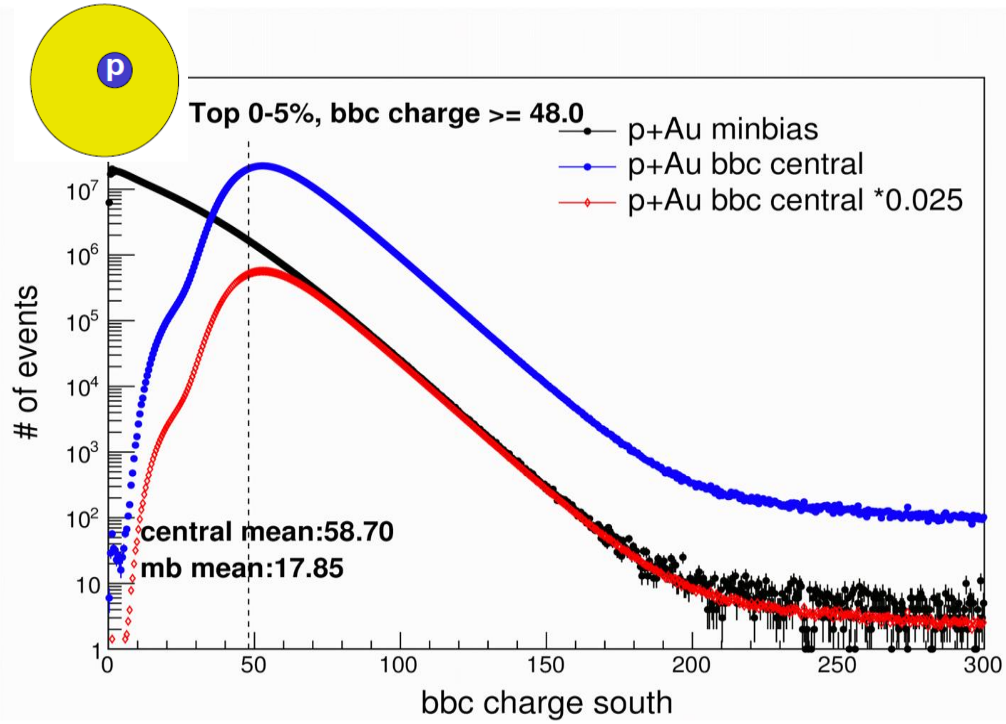


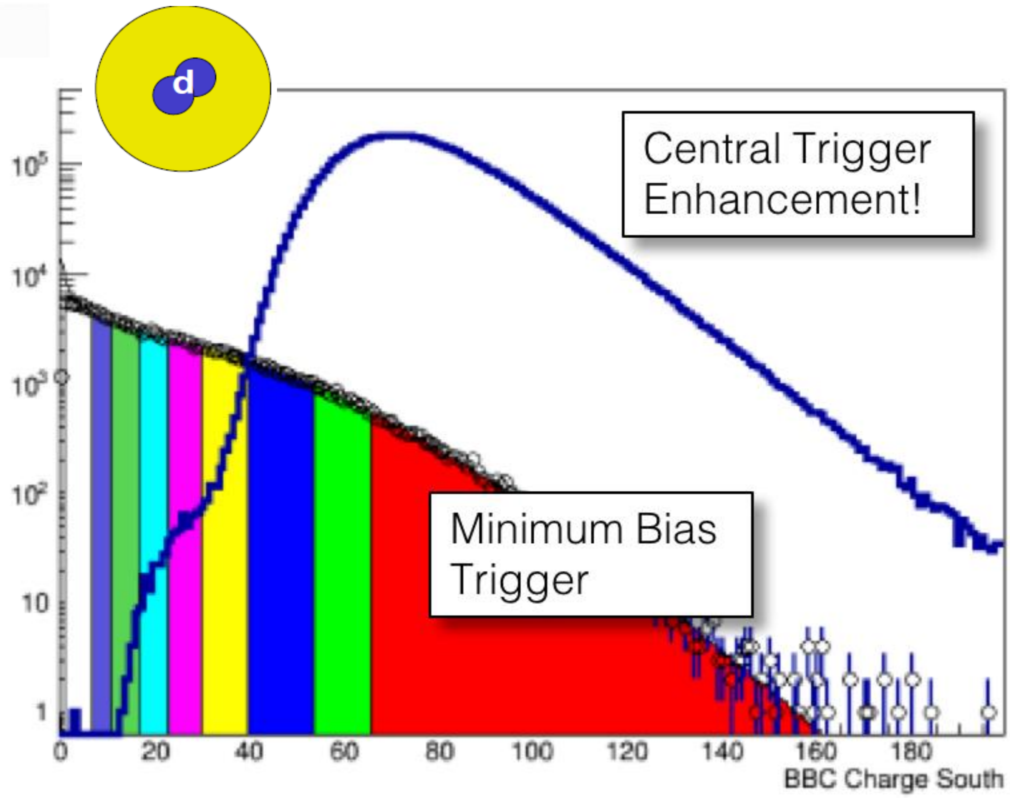
Initial state

Quark Gluon Plasma?
thermally equilibrated ?

Hadronic phase
and freezeout

High-multiplicity triggered event samples





collision system (200 GeV)	increase in central events
p+Au *PRC 95 (2017) 034910*	x40
d+Au *preliminary*	x15
^{3}He+Au *PRL 115, 142301 (2015)*	x10

2016 d+Au $\sqrt{s_{NN}}$ (GeV)	Number of Central Events Recorded
20	15 Million
39	137 Million
62.4	131 Million
200	636 Million

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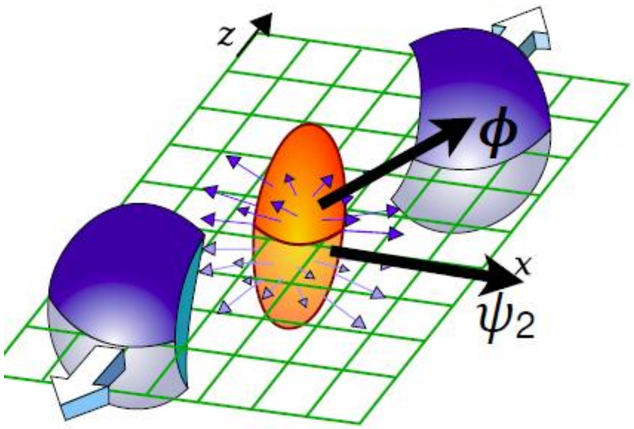
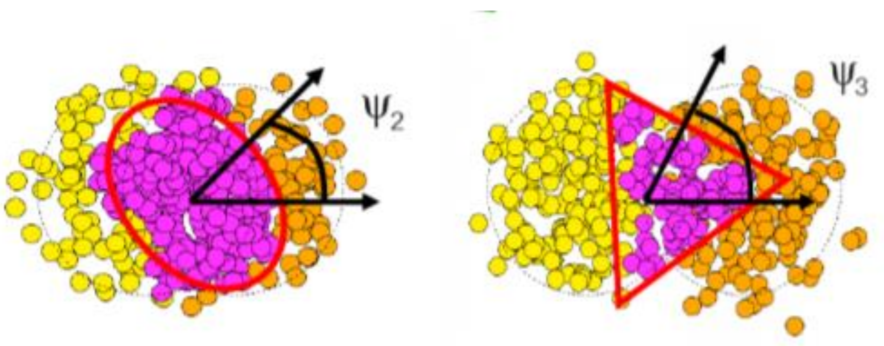
Experimental methods in PHENIX

Event plane: determined at large backward pseudorapidity
Particles: tracked over a large pseudorapidity range

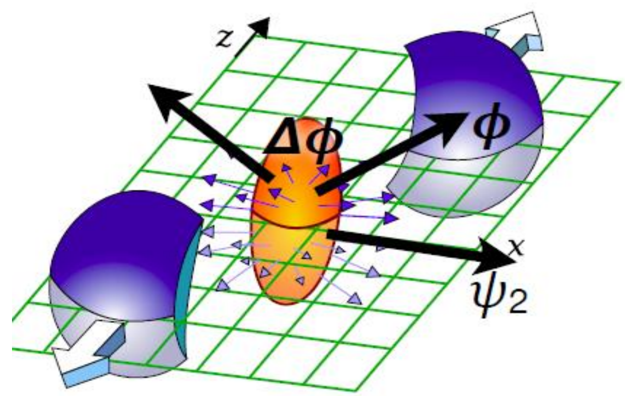
$$dN/d\phi = 1 + \sum_n 2v_n \cos(n(\phi - \Psi_n))$$





Or
2-particle correlations comprised of:
1) particle at mid-rapidity
2) energy cluster in BBC
3) tracks in FVTX

pair amplitude modulation
$$c_n = v_n^a \times v_n^b$$



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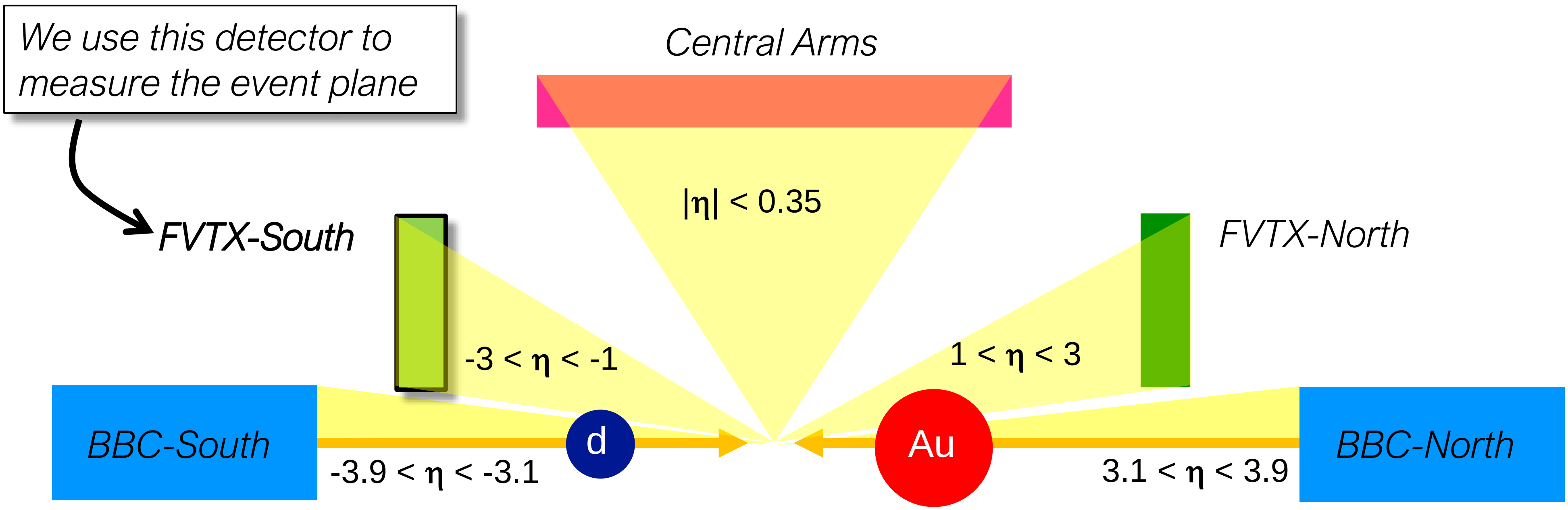
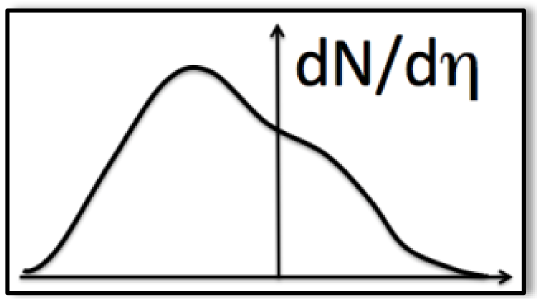
EP: Measurements of $v_n(p_T)$ at mid rapidity





$$v_2 = \frac{\langle \cos 2(\phi - \Psi_2) \rangle}{\mathrm{Res}(\Psi_2)}$$

To optimize Resolution, we use:

- Central Arms
- FVTX-South
- BBC-South

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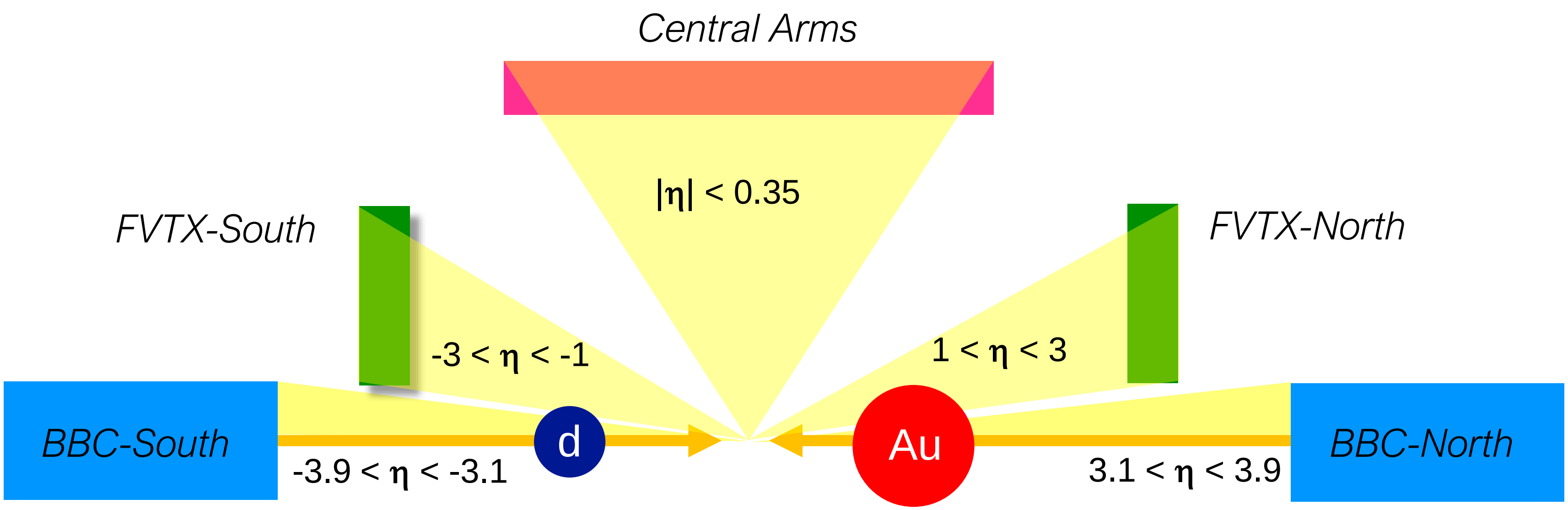
2-particle correlations



- various detector combinations are used
- 2-particle correlations used to:
  - estimate nonflow (in conjunction with min bias pp data)
  - look for the ridge
  - in some cases -> to confirm the EP measurements

RESULTS

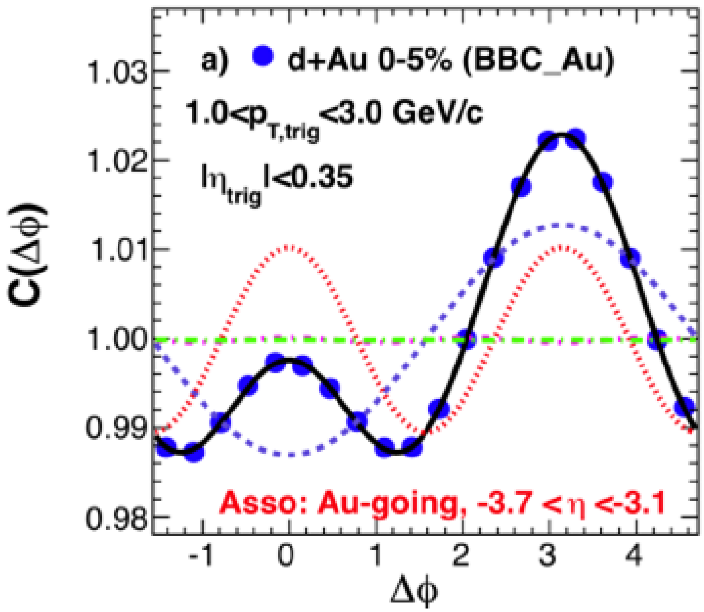
1. **Ridge in different systems**

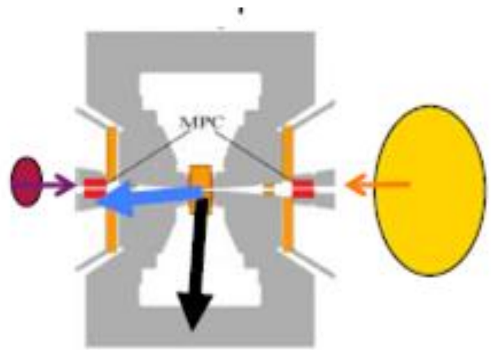
2. Geometry scan: flow of inclusive particles

3. Geometry scan: flow of identified particles

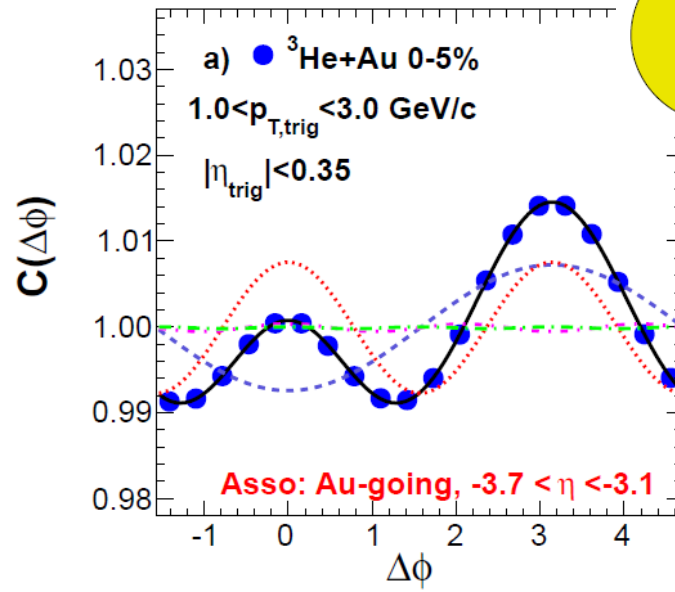
Ridge (d/^{3}He+Au), and no clear ridge pA

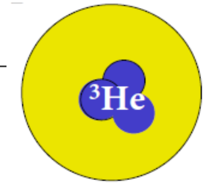
Phys. Rev. Lett. 114, 192301, 2015



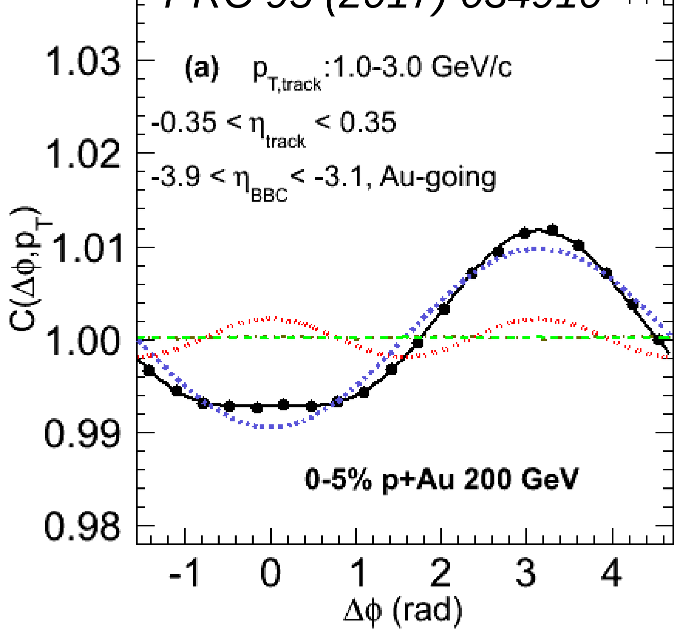


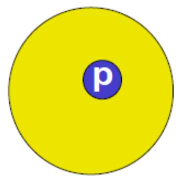
Phys. Rev. Lett. 115, 142301 , 2015



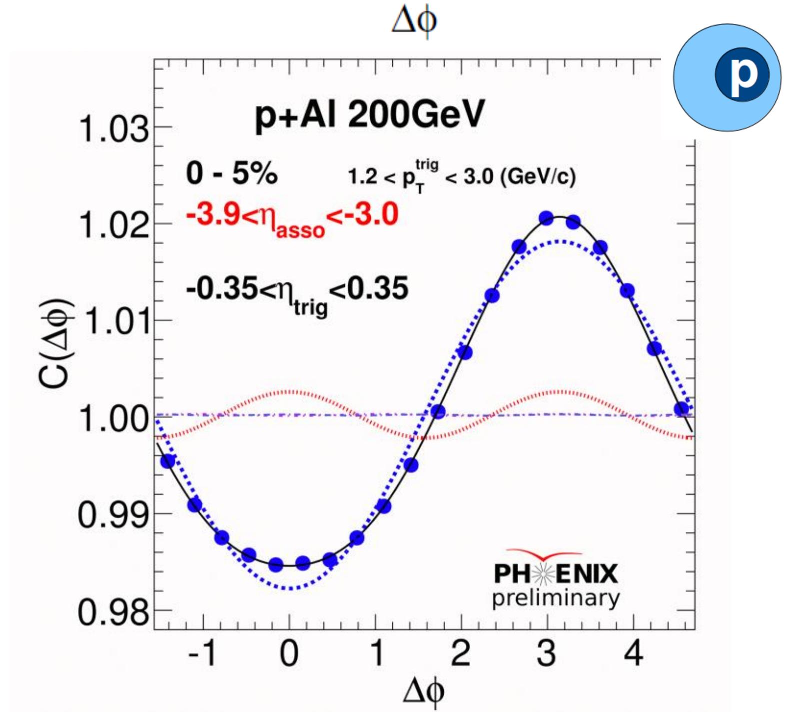


PRC 95 (2017) 034910

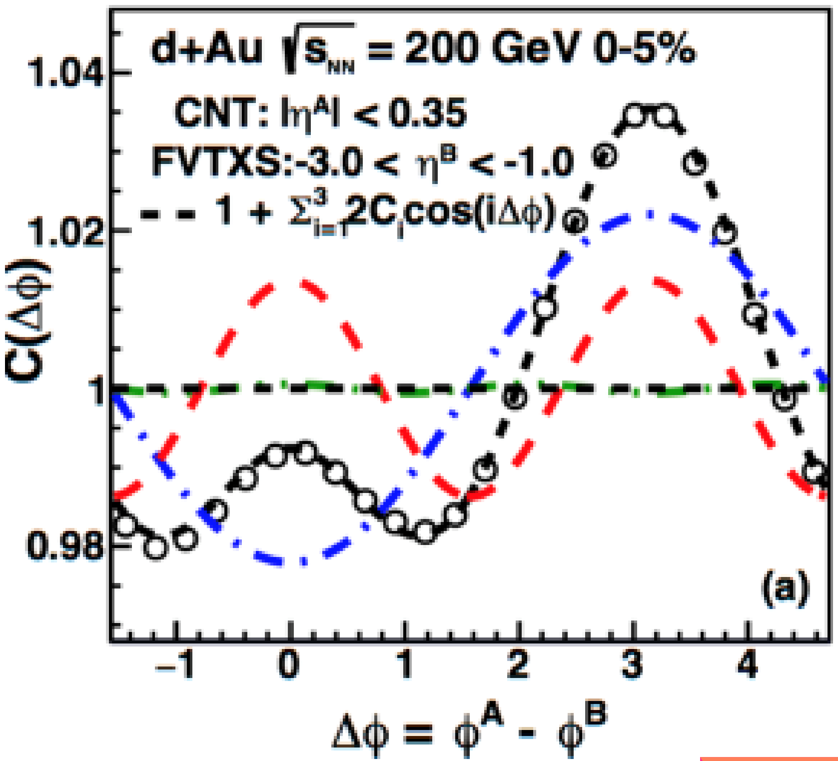


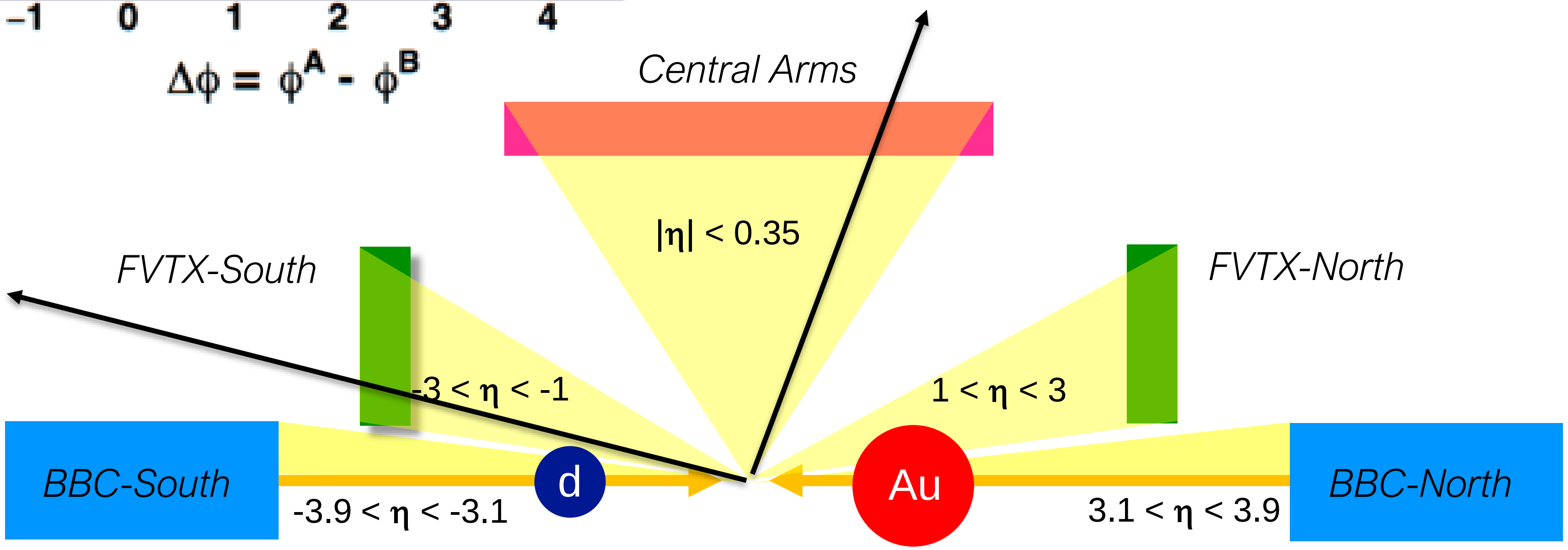


$|\Delta\eta|>2.75$

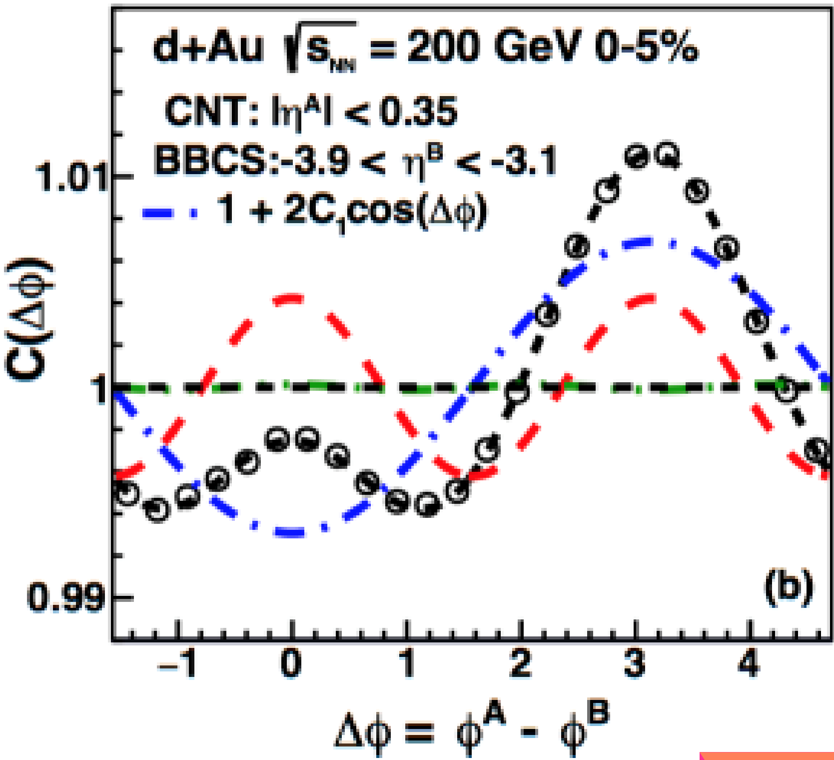


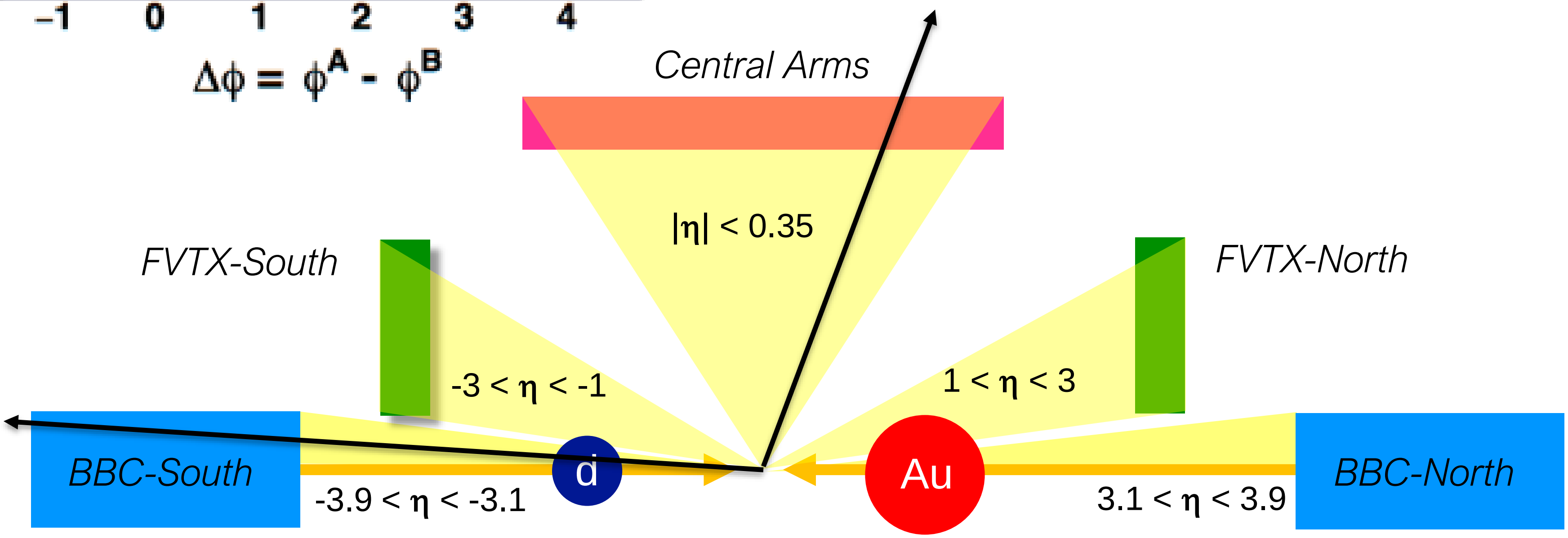
d+Au at 200 GeV: ridge evolution with Δη





d+Au at 200 GeV: ridge evolution with Δη





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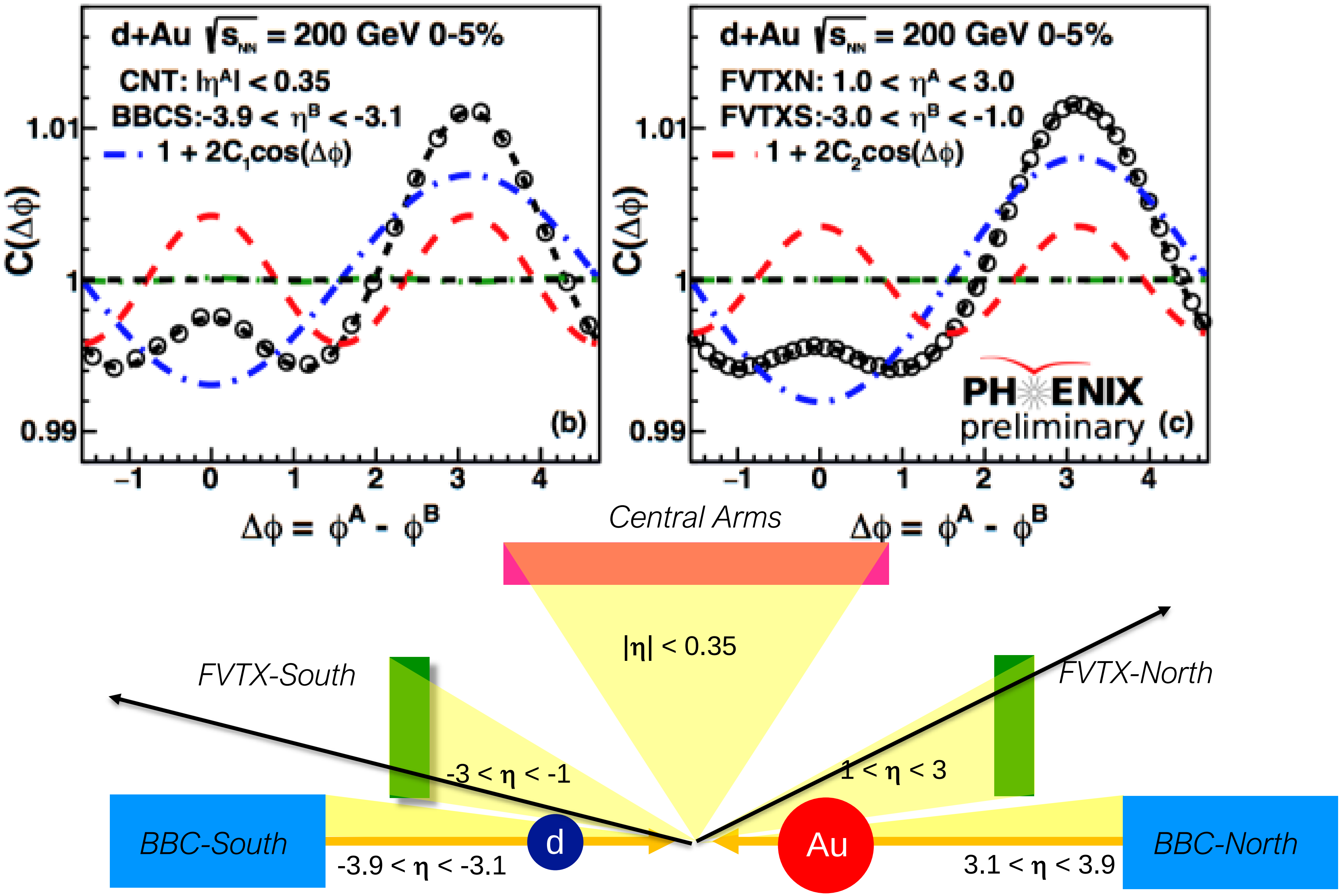
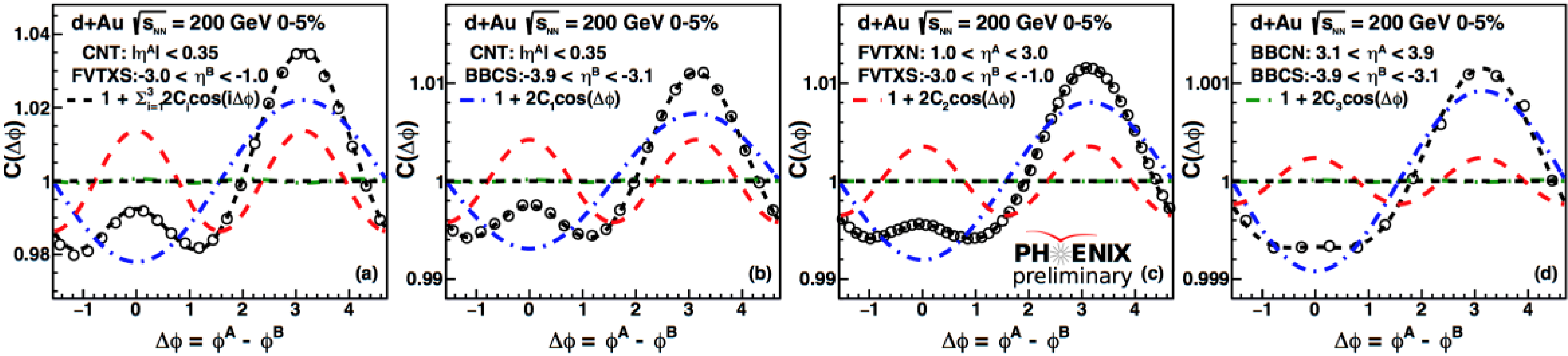
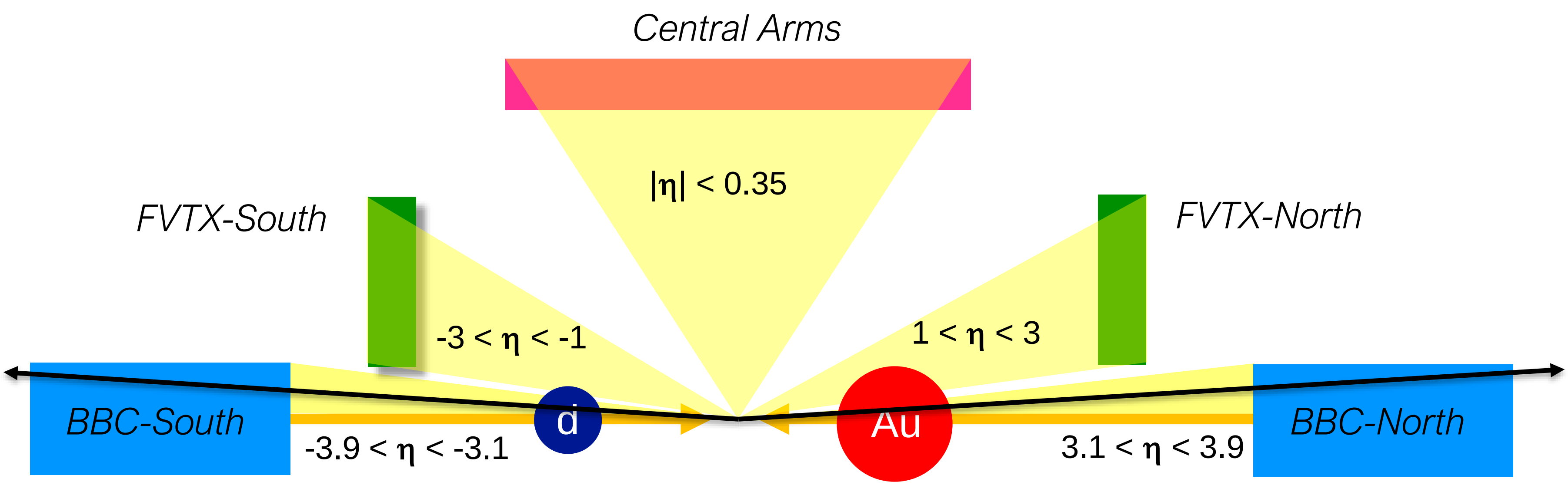
d+Au at 200 GeV: ridge evolution with Δη



d+Au at 200 GeV: ridge evolution with Δη





A clear ridge is seen with all detector combinations, even for **$\Delta\eta > 6.2$**

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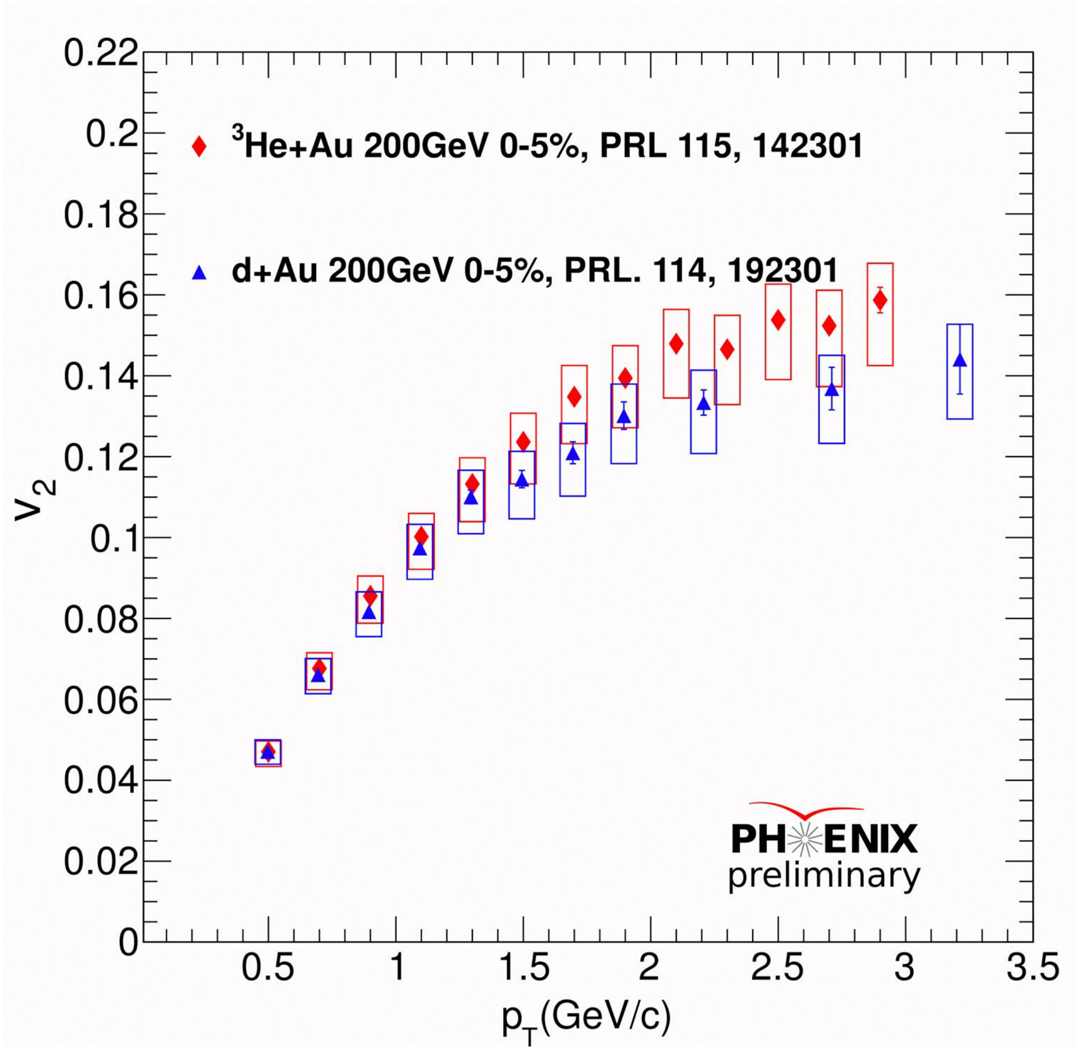
RESULTS

1. Ridge in different systems at 200 GeV
   - Pronounced ridge in d/^{3}He+Au, but not in p+A
   - In d+Au, the ridge extends over $\Delta\eta > 6.2$
2. **Geometry scan: flow harmonics of inclusive particles**
3. Geometry scan: flow harmonics of identified particles

Charged hadron v_2: d/^{3}He+Au



- $v_2(^3\mathrm{HeAu}) \sim v_2(\mathrm{dAu})$
- $\varepsilon_2(^3\mathrm{HeAu}) = 0.50$, $\varepsilon_2(\mathrm{dAu}) = 0.54$

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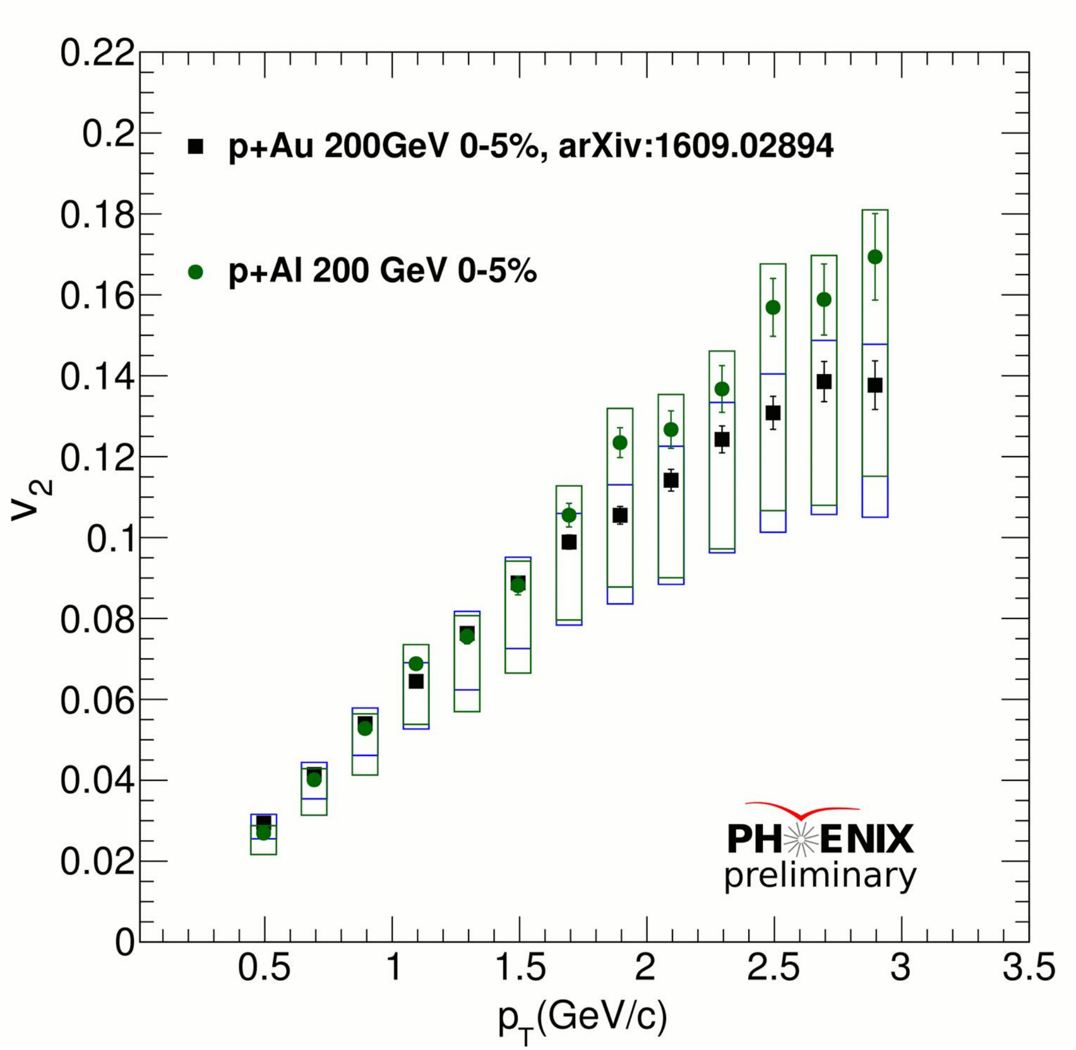
Charged hadron v_2: p+Au, p+Al

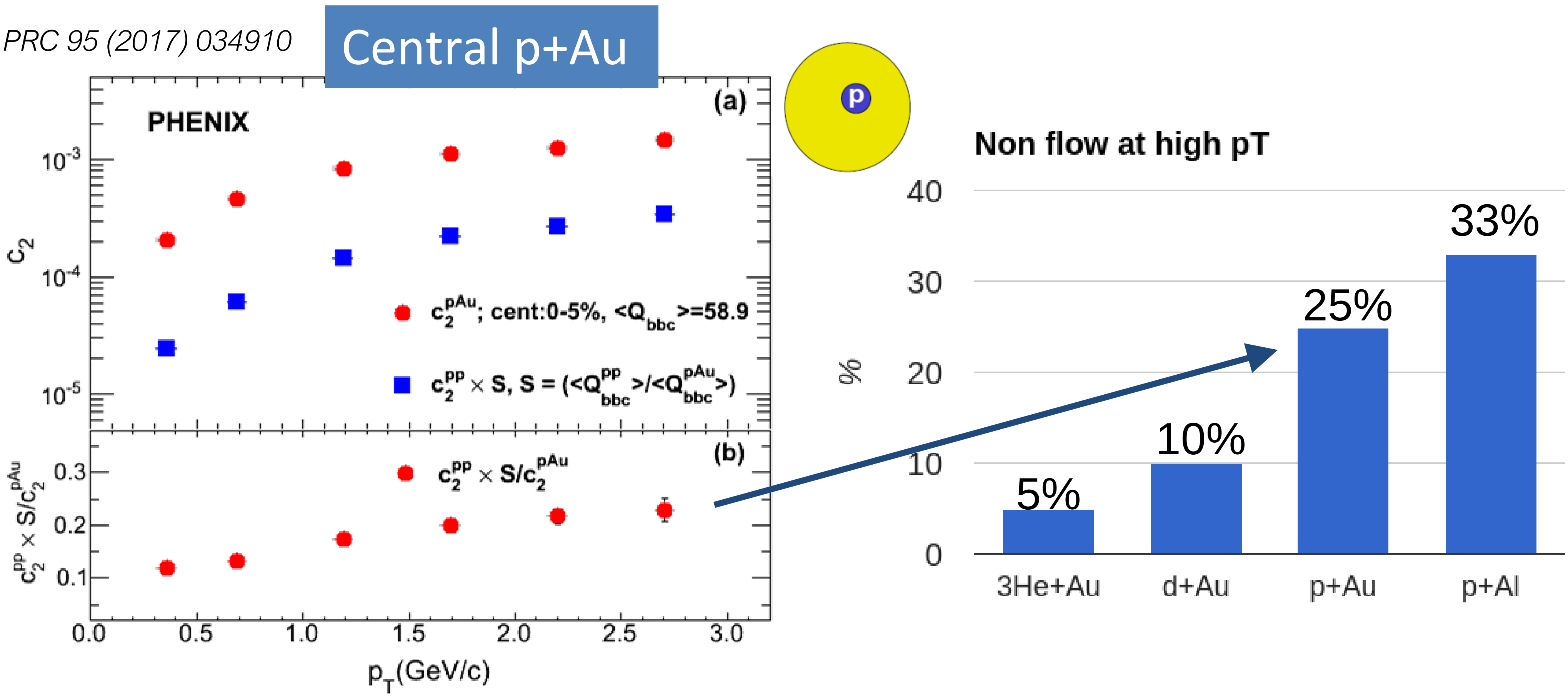


(growing) asymmetric systematics from nonflow

- v_2(pAu) ~ v_2(pAl)
- ε_2(pAu) = 0.23, ε_2(pAl) = 0.30

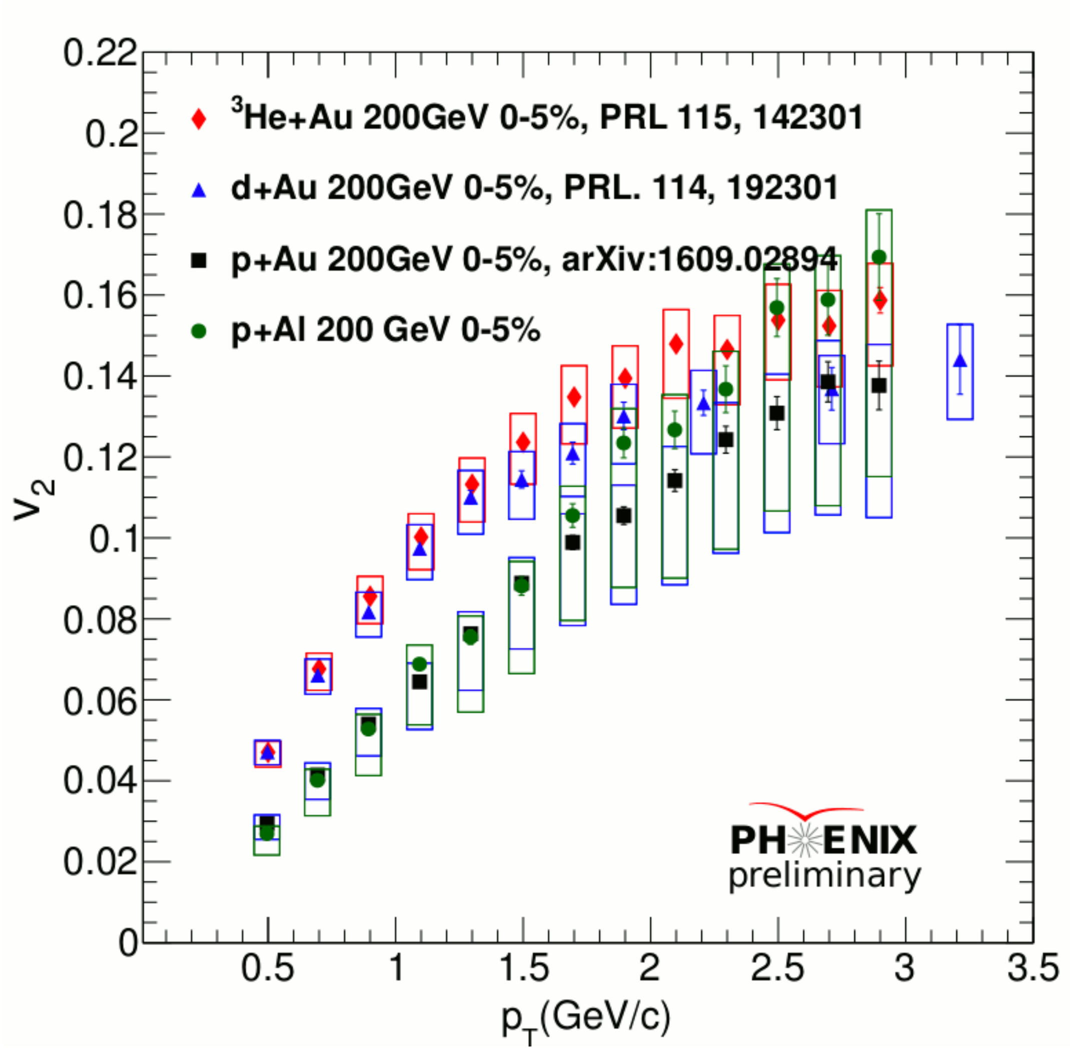
Nonflow estimation based on pp data

PRC 95 (2017) 034910



- Correlations in pp minbias data scaled by multiplicity
- Not subtracted - cited as a systematic uncertainty

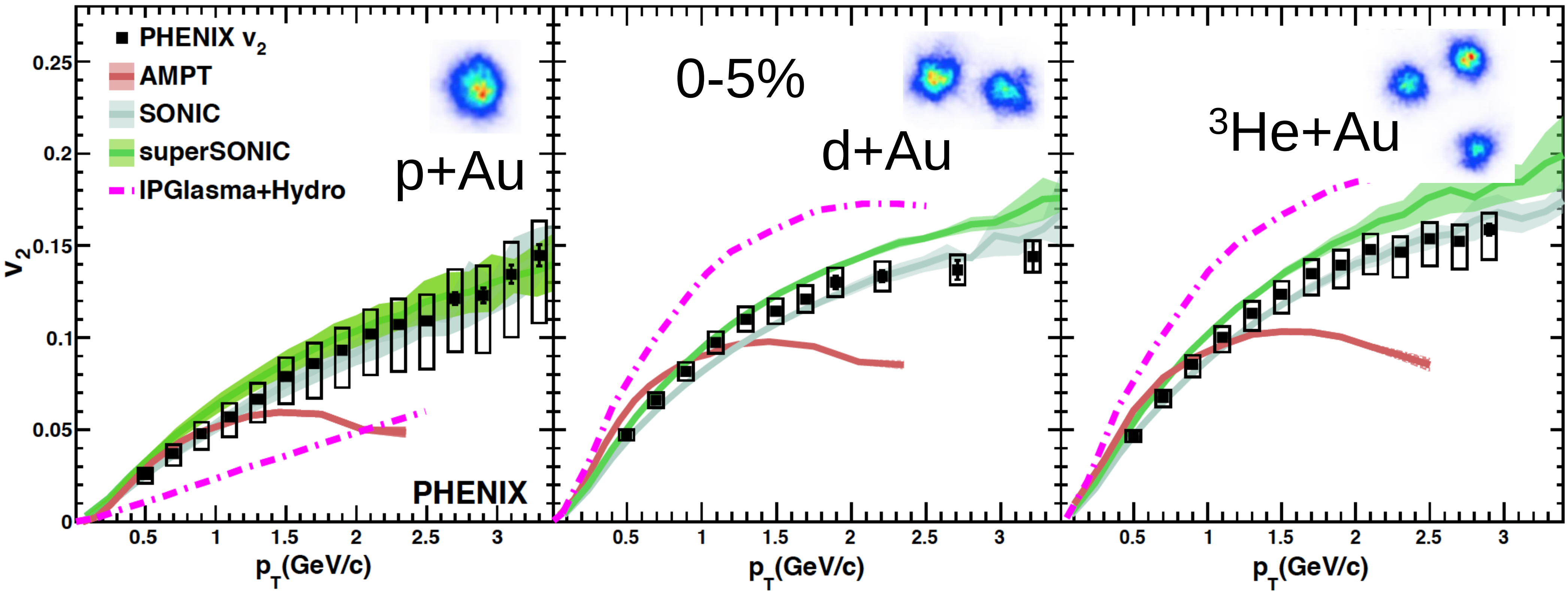
Charged hadron v_2: systems group by ε



- $v_2(^3HeAu) \sim v_2(dAu) > v_2(pAu) \sim v_2(pAl)$
- Geometry control works!

Geometry engineering, v_2 (p_T), and models

PRC 95 (2017) 034910 *PRL 114, 192301, (2015)* *PRL 115, 142301, (2015)*

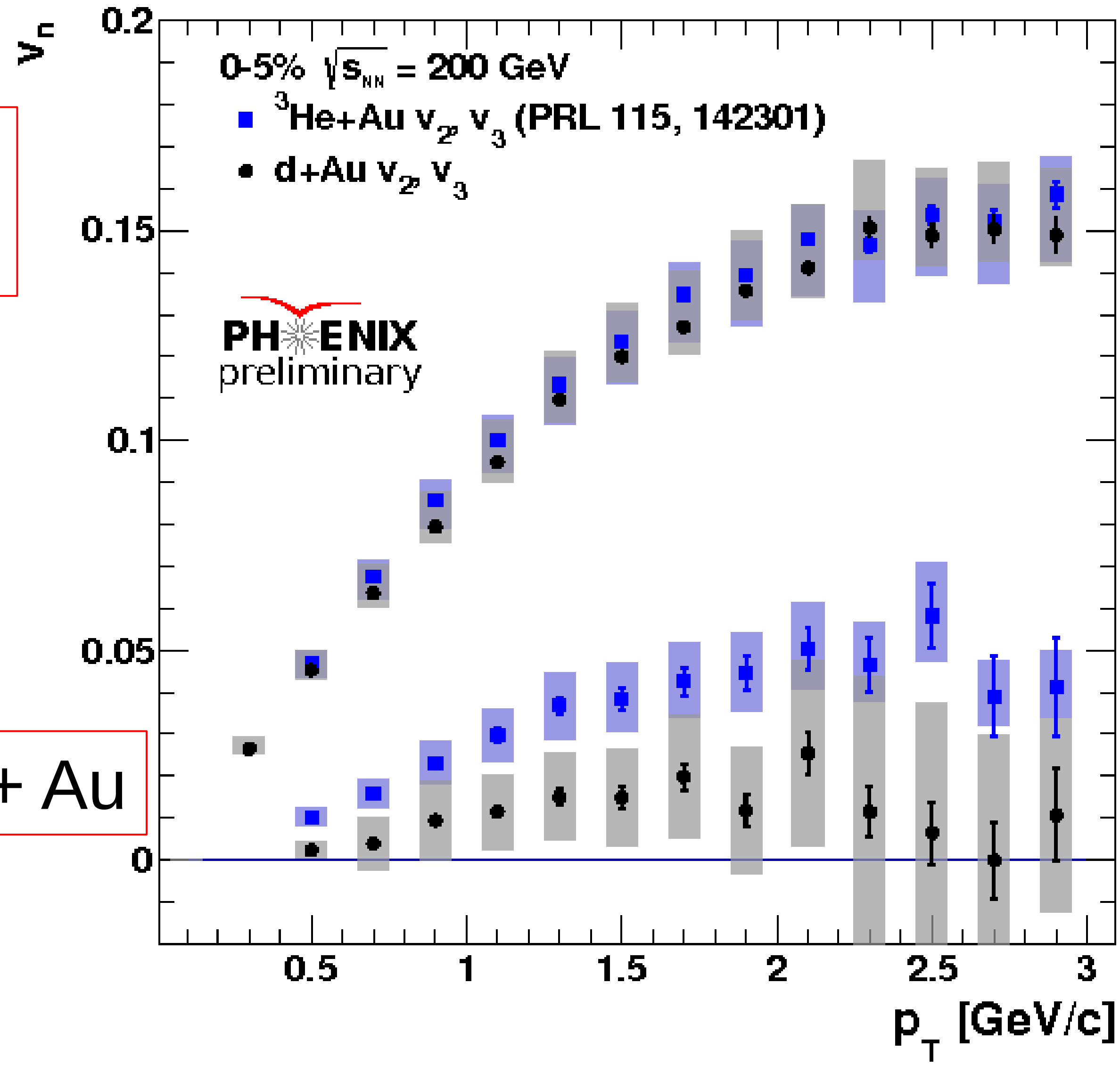


- Hydrodynamics with small η/s works!
- AMPT: weakly coupled partonic cascade+quark coalescence+hadronic cascade also works at low p_T.
- Other observables ?

Triangular flow at 200 GeV in different systems: insights about the role of preflow

v_2 in d/^{3}He+ Au
Nearly identical

v_3 smaller in d+ Au

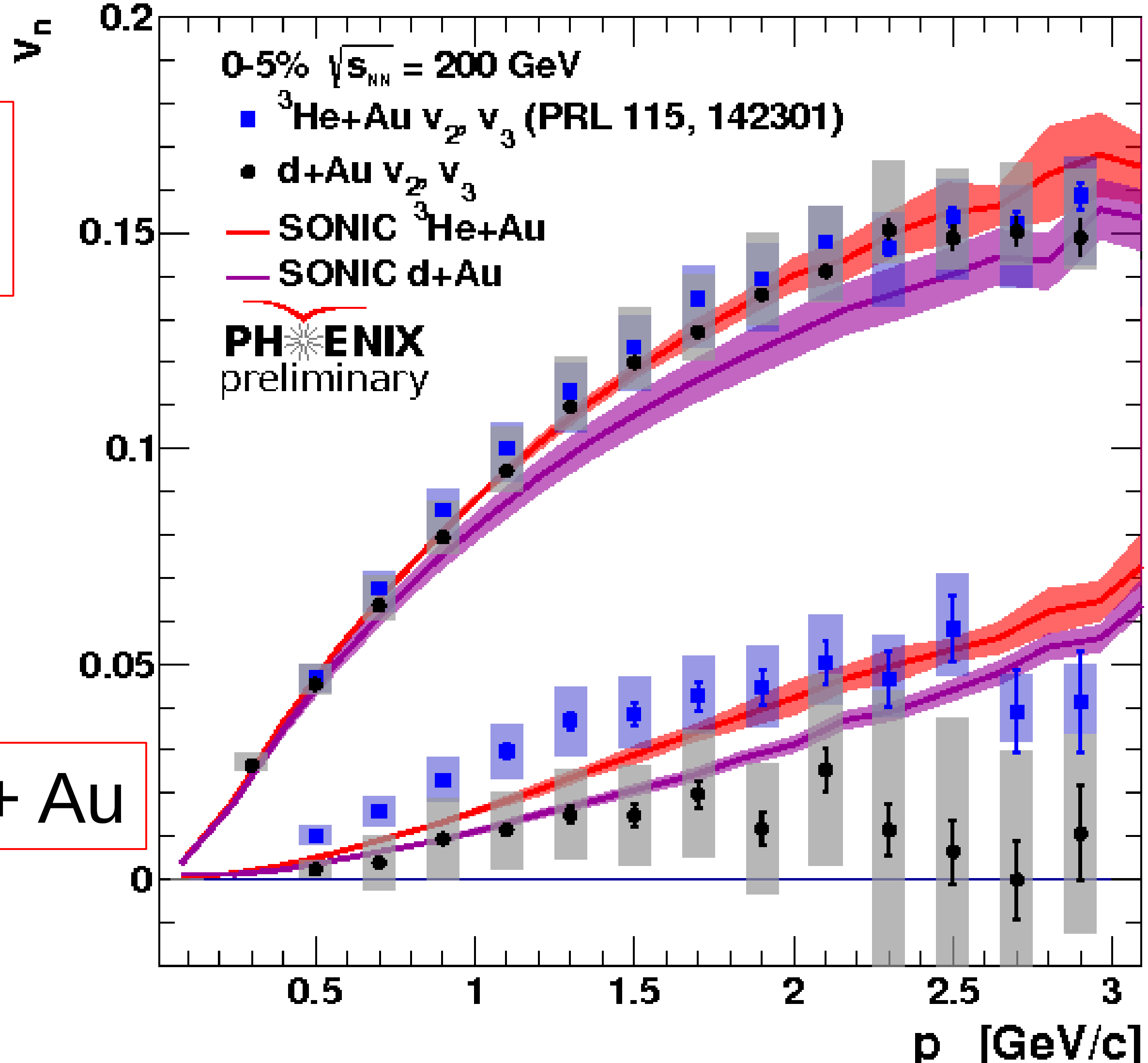


v_2

v_3

Triangular flow at 200 GeV in different systems: insights about the role of preflow

v_2 in d/^{3}He+ Au
Nearly identical



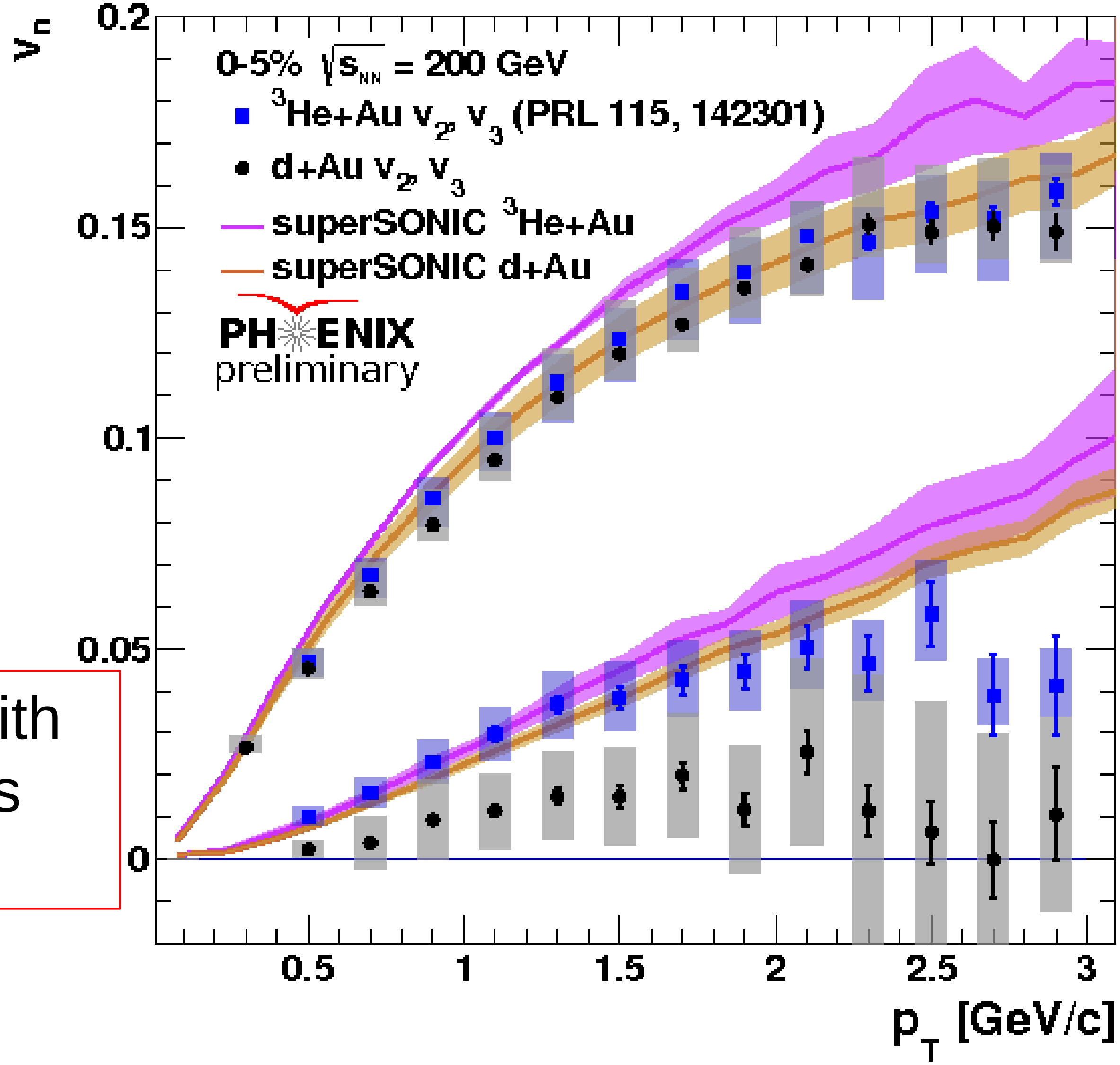
v_2

v_3 smaller in d+ Au

v_3

- Trends well described with hydro without preflow

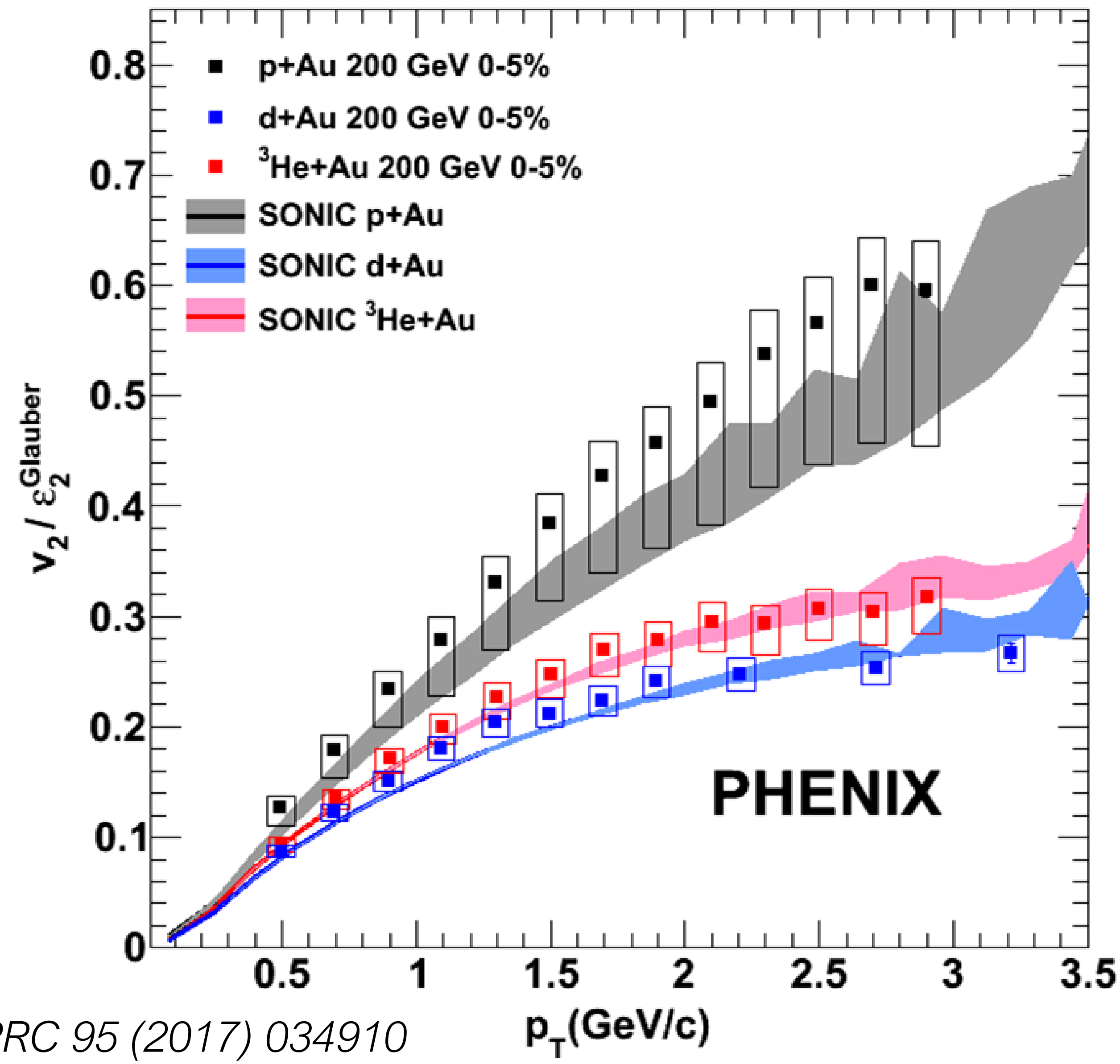
Include pre-equilibrium flow



worse agreement with data when preflow is included

Relative contributions from pre-equilibrium and QGP need retuning ?

v_2/ε_2 in systems with different geometry



PRC 95 (2017) 034910

The v_2/ε_2 in p+Au is higher than that of d+Au and ^{3}He+Au collisions

^{3}He/d+Au – some events hot spots never connect and so $\varepsilon_2 \rightarrow v_2$ translation incomplete

This behavior is within the expectation of SONIC model, which includes Glauber initial geometry and viscous hydro evolution.

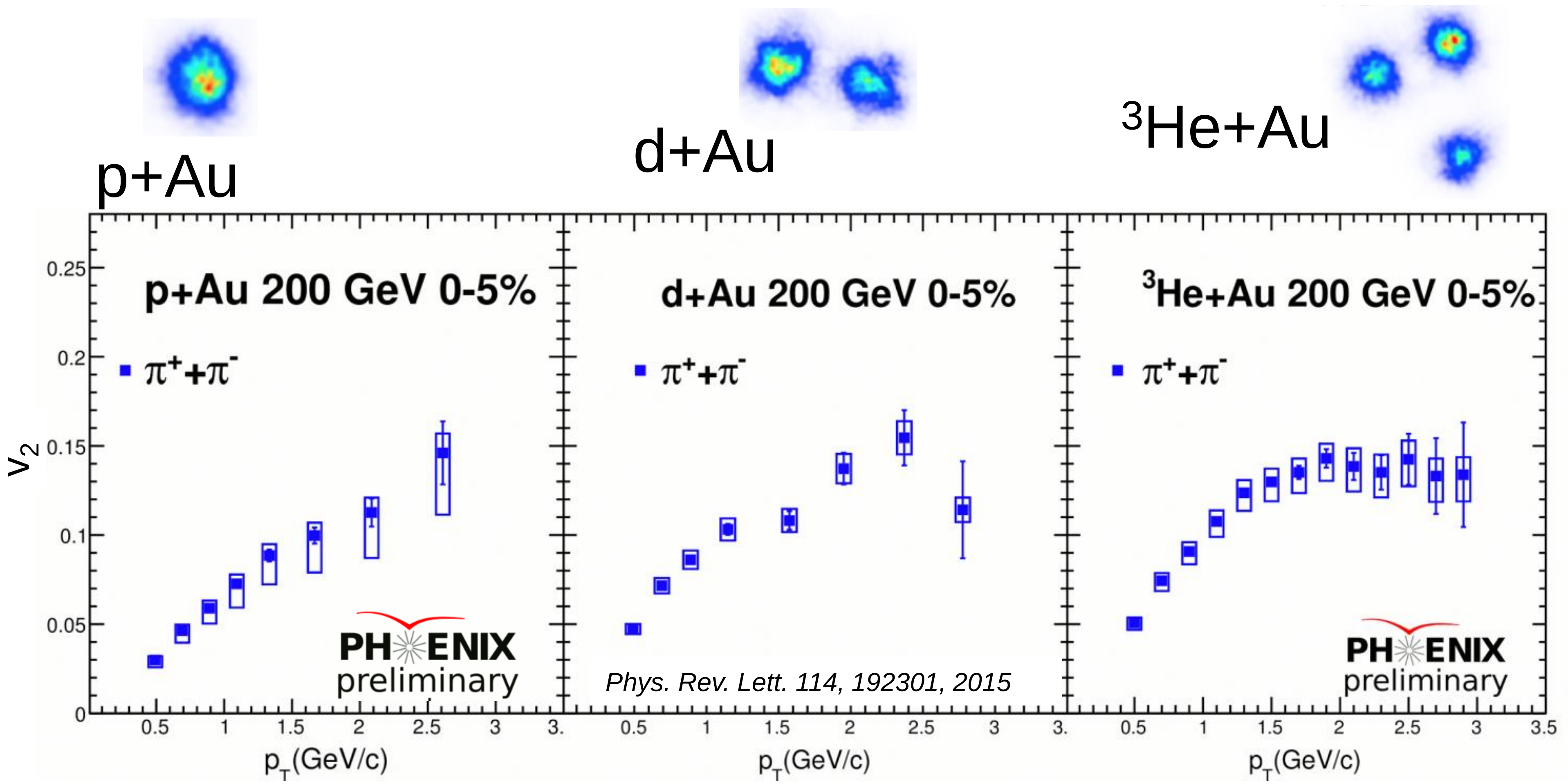
RESULTS

1. Ridge in different systems at 200 GeV

2. Geometry scan: flow harmonics of inclusive particles

3. **Geometry scan: flow harmonics of identified particles**

Identified particle v_2 in different systems



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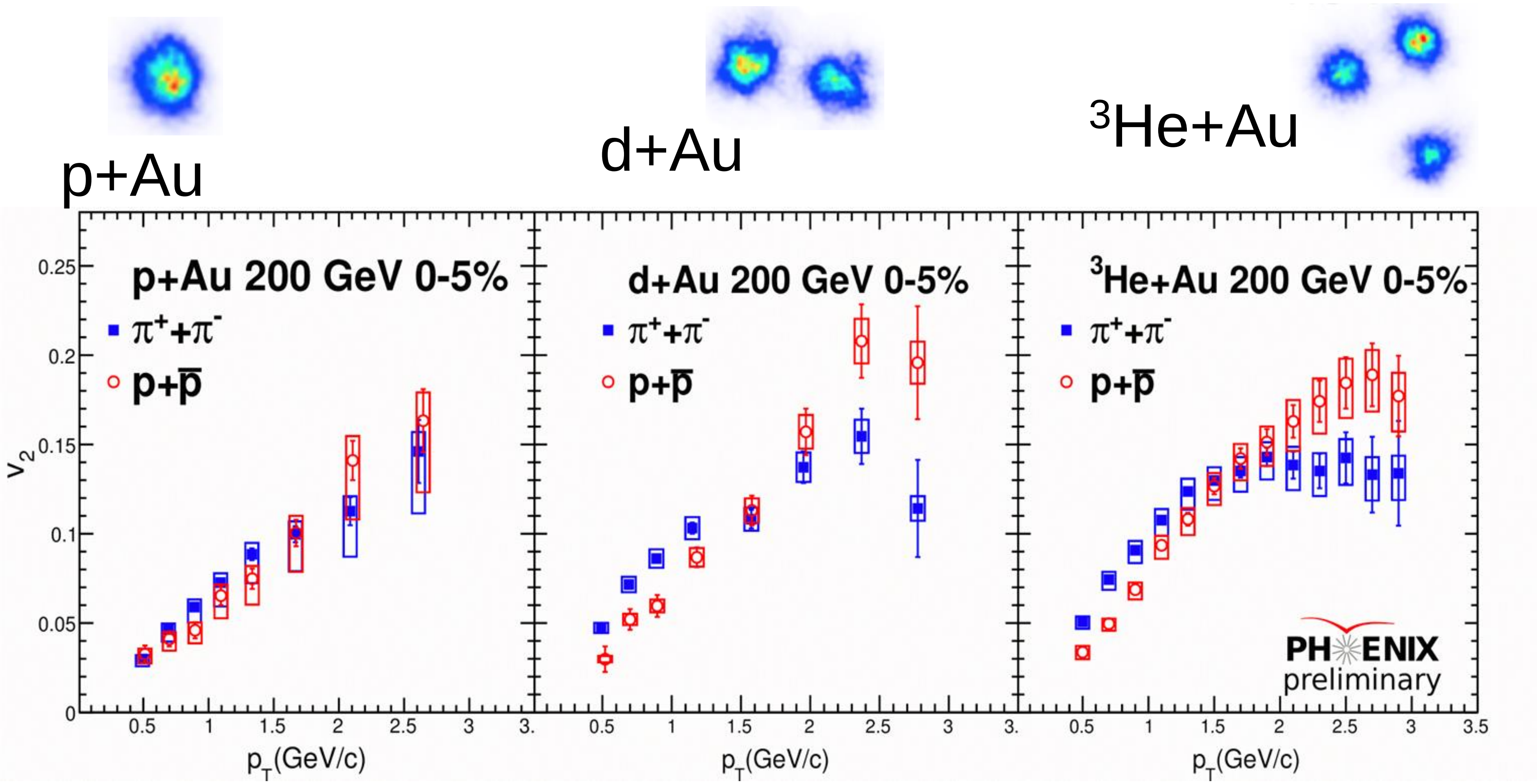
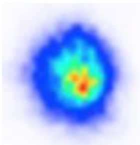
Identified particle v_2 in different systems

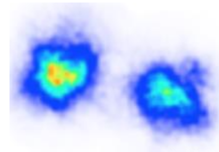


- Mass-ordering in all three systems
- Less pronounced in p+Au than in d+Au and ^{3}He+Au

NCQ scaling in different systems

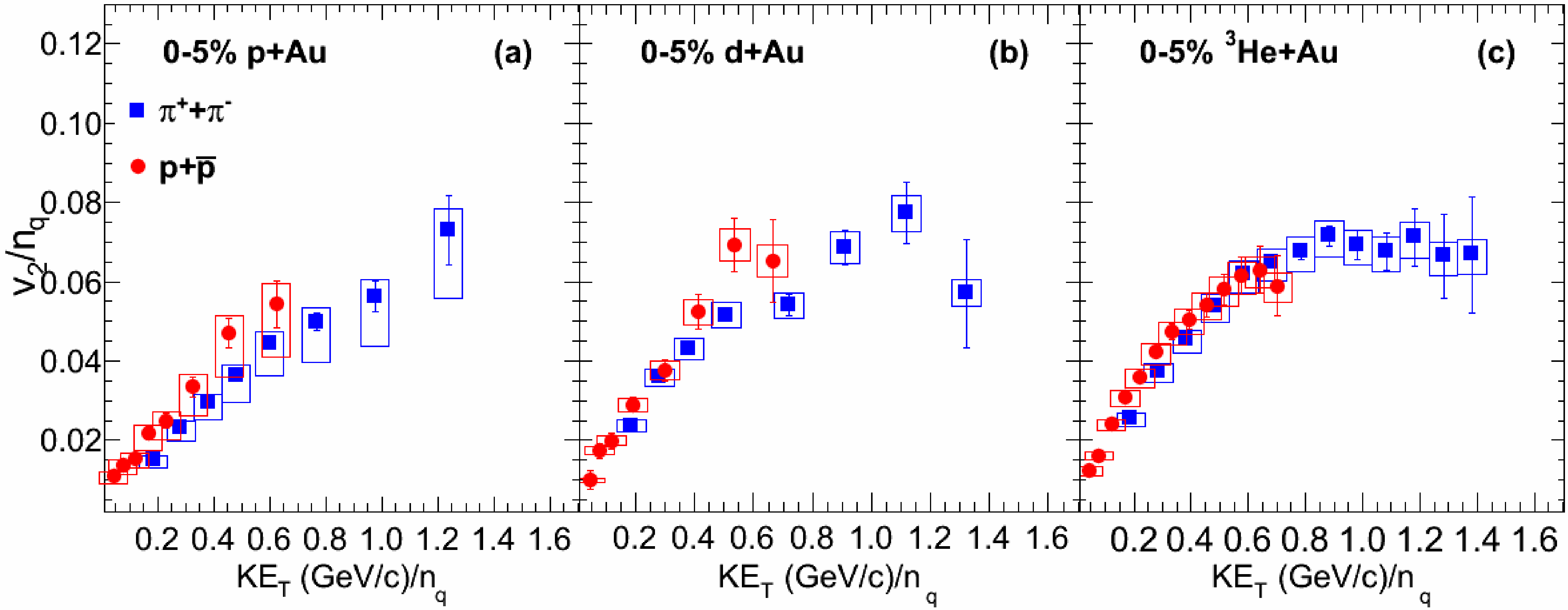


p+Au



d+Au

^{3}He+Au



- Scaling works in d/^{3}He+Au well as in A+A collisions
- The difference became larger for p+Au

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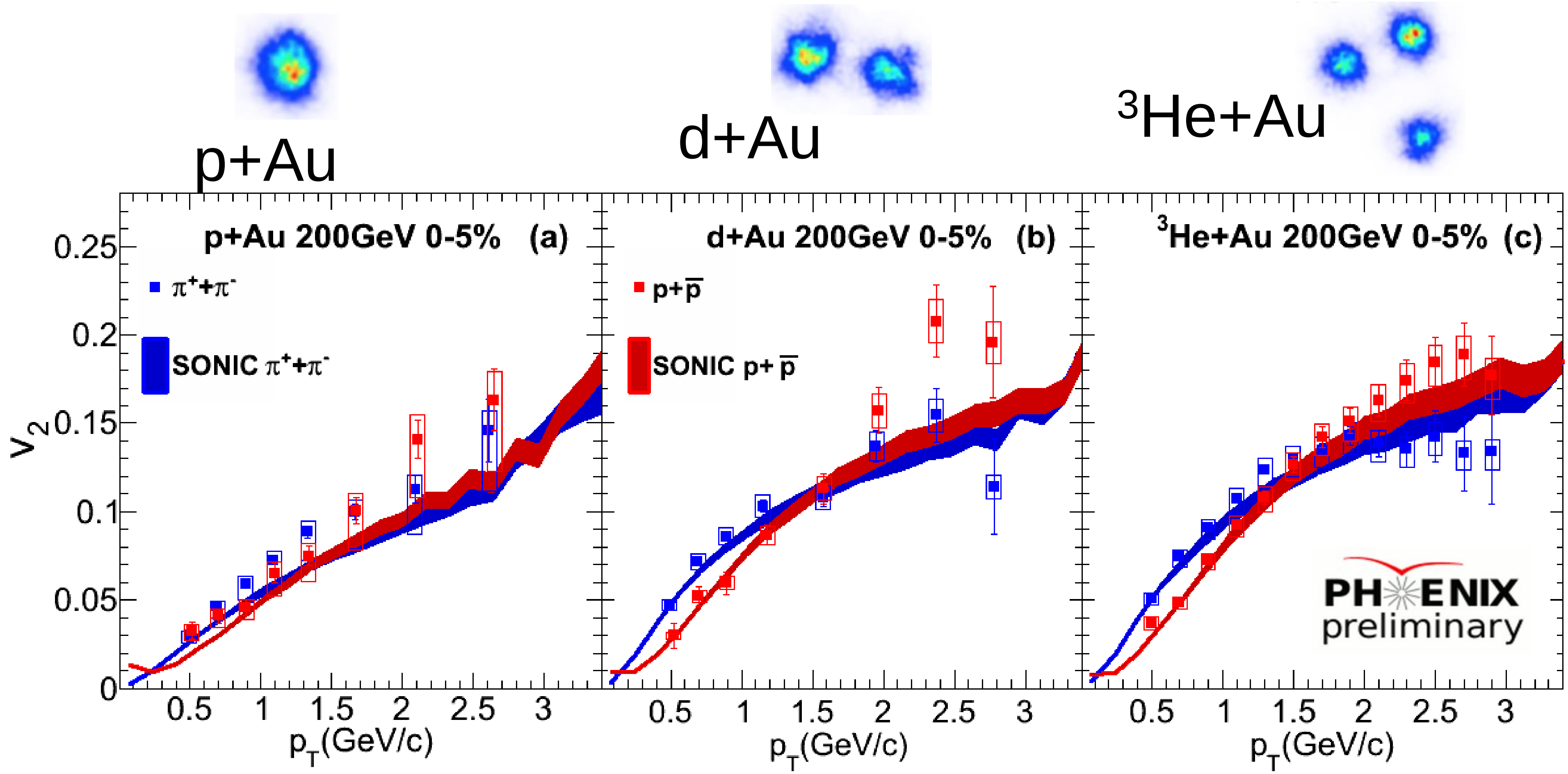
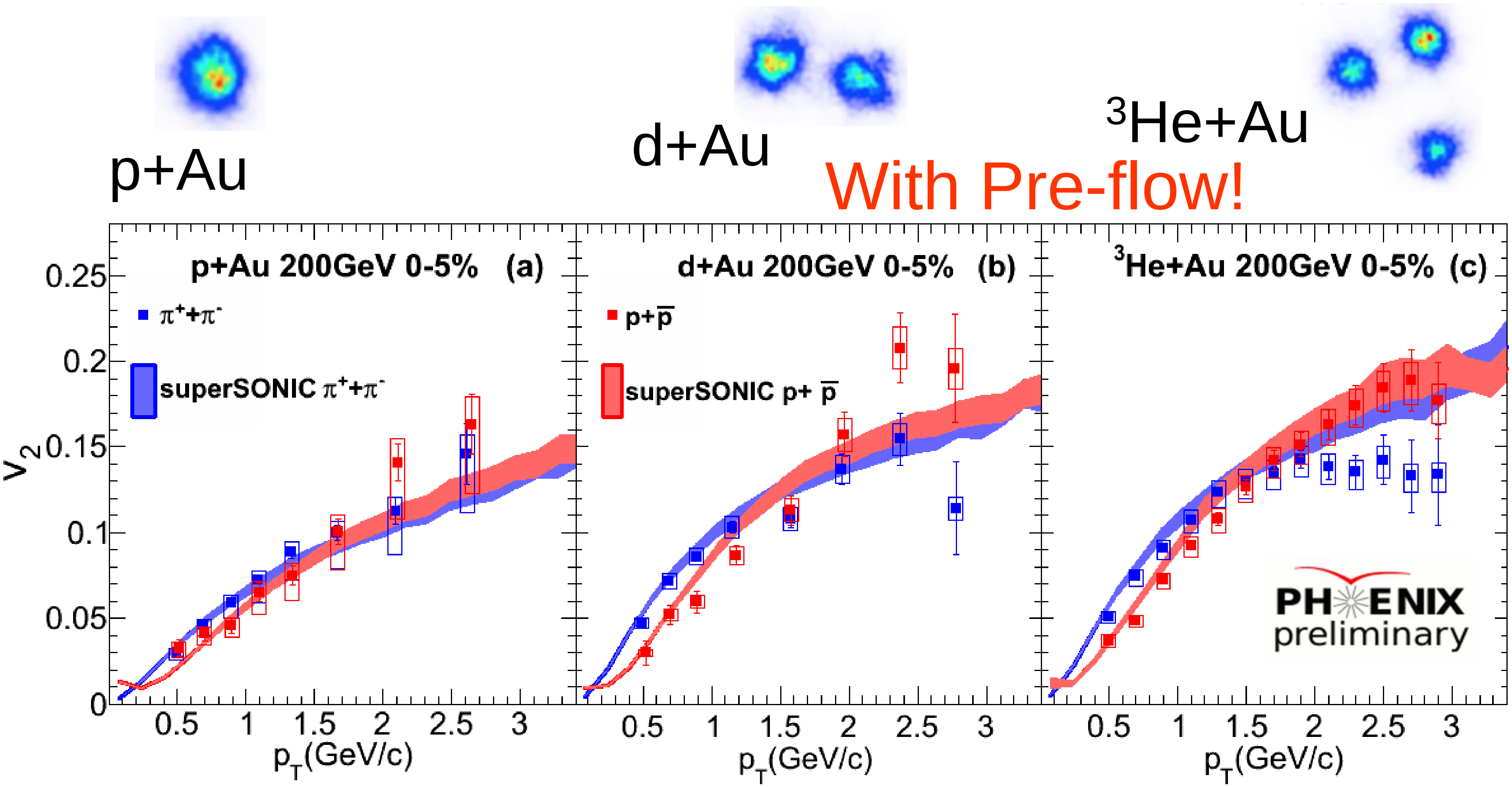
Identified particle v_2 compared to hydro



- Well described p/d/^{3}He+Au results at low p_T
- Smaller split at p+Au is predicted which implies smaller radial push
- High p_T mass split not seen, recombination not included

Identified particle v_2 compared to hydro



- Well described p/d/^{3}He+Au results at low p_T
- High p_T mass split is not seen, recombination not included

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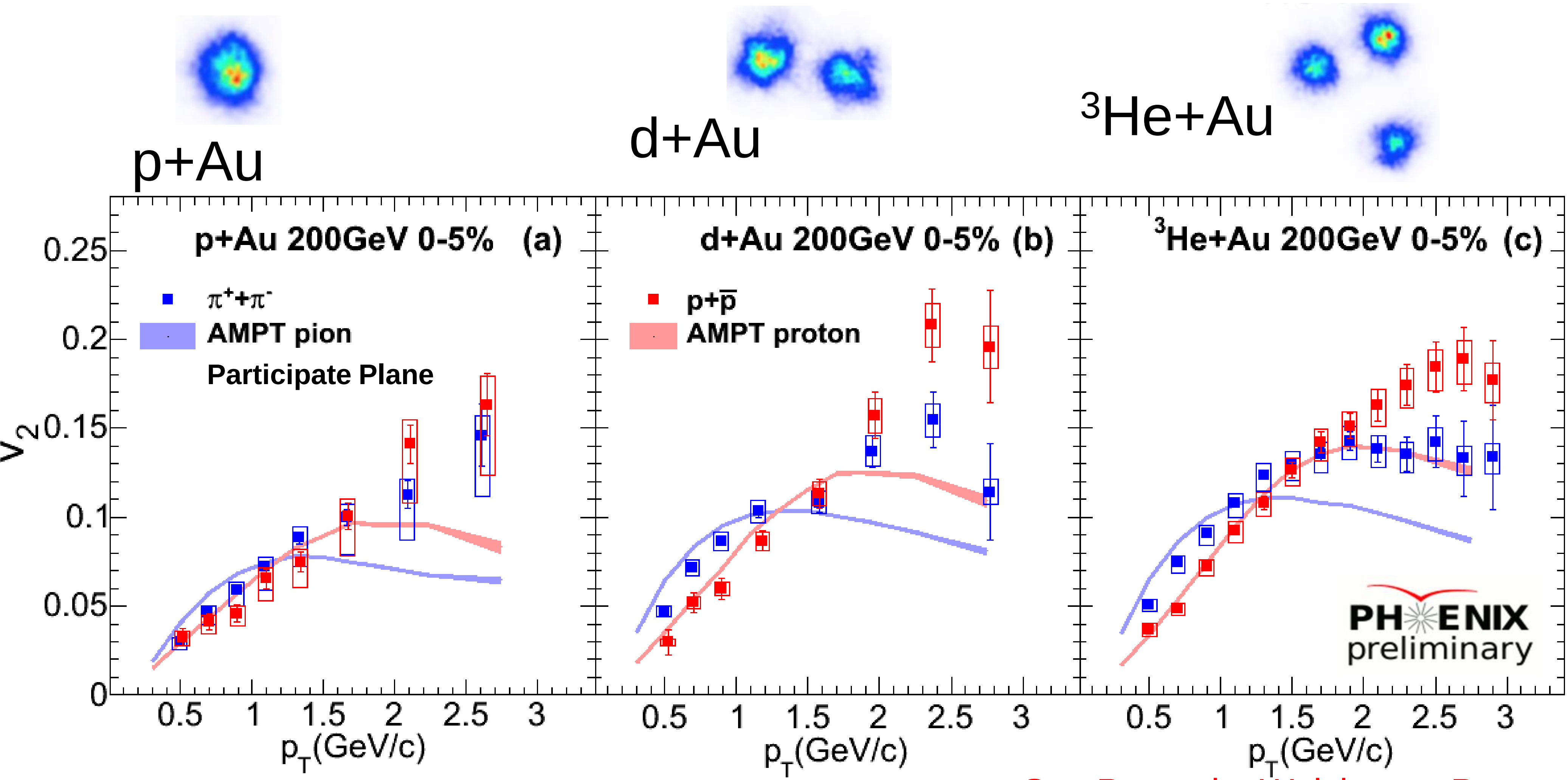
Identified particle v_2 compared to AMPT



See Poster by Weizhuang Peng

- Overall trend is predicted, could be explained by quark coalescence + hadronic rescattering
- v_2 magnitude under-predicted at high p_T

Origin of the mass splitting of elliptic anisotropy in a multiphase transport model - Li, Hanlin et al. Phys.Rev. C93 (2016) no.5, 051901

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Results and Conclusions

1. Ridge in different systems at 200 GeV
   - Pronounced ridge in d/^{3}He+Au, but not in p+A
   - In d+Au, the ridge seen for $\Delta\eta > 6.2$ –> **truly long-range**

2. Geometry scan: flow of inclusive particles
   - $v_2(p_T)$ and $v_3(p_T)$ follow initial geometry
   - Hydro and AMPT describe the data up to p_T ~ 3 or 1 GeV
   - v_3 in dAu and ^{3}HeAu discriminate against preflow/flow

3. Geometry scan: flow of identified particles
   - Identified particle $v_2(p_T)$ shows mass ordering
   - The splitting of pion and proton in low p_T in three systems is predicted by AMPT and hydro models

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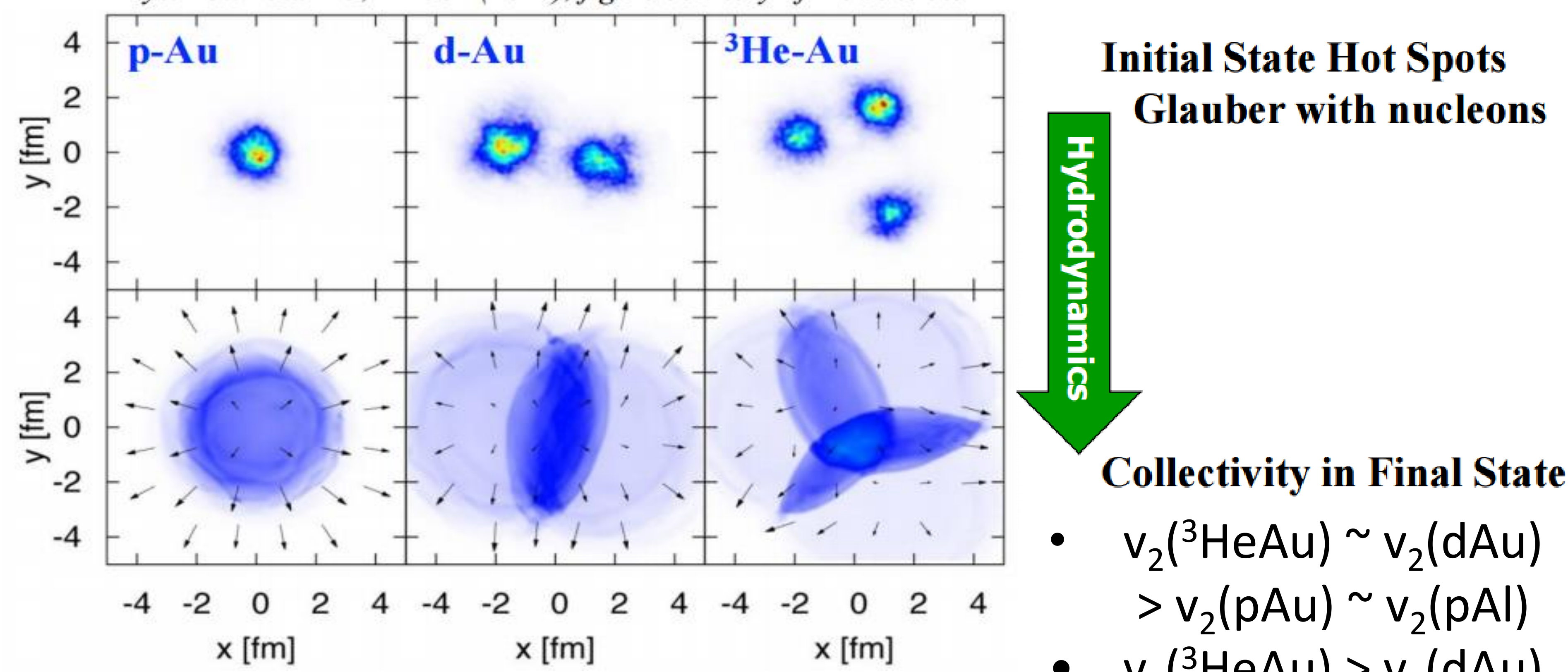
BACKUP

Geometry handles on collectivity in small systems

Geometry Engineering

Phys. Rev. Lett. 113, 112301 (2014), figure courtesy of B. Schenke



- $v_2(^3HeAu) \sim v_2(dAu) > v_2(pAu) \sim v_2(pAl)$
- $v_3(^3HeAu) > v_3(dAu)$

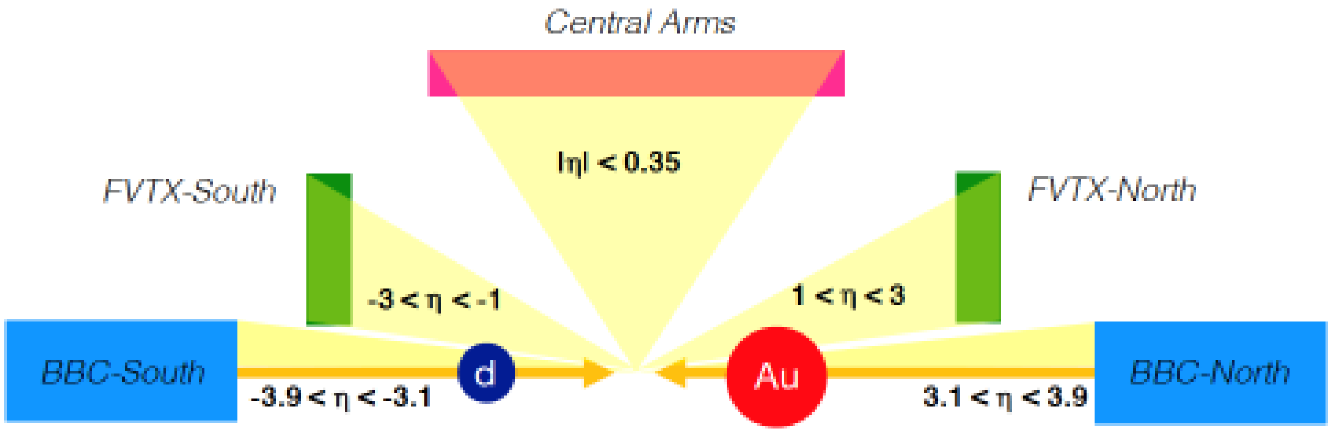
Table 6: Summary of the systematic uncertainties on the v_2 vs p_T measurements at 200, 62.4, and 39 GeV.

Sys	200	62.4	39
Double interactions	+9.4%	$<1\%$	$<1\%$
Event Plane	4.5%	4.5%	4.5%
East vs West	1.6%	3.6%	5.9%
PC3 Match	1%	1%	1%
ϕ shift	1%	1%	10% $p_T < 1$ and 5% $p_T > 1$
Total	$^{+10.6\%}_{-4.9\%}$	$\pm 5.8\%$	$\pm 7.5\%$

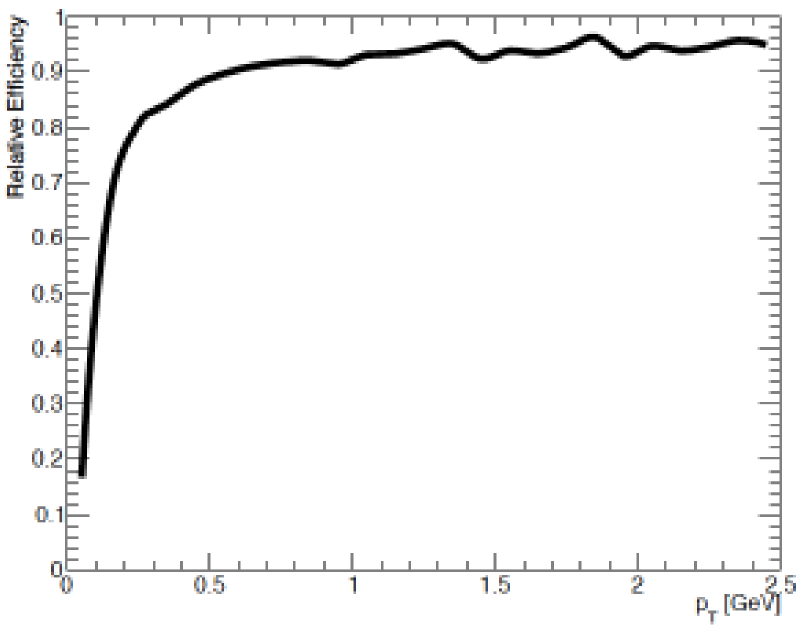
Table 8: A summary of the systematic uncertainties applied to the measurement of v_2 vs η in 200, 62.4, and 39 GeV d+Au collisions.

Sys	Type	200	62	39
Double Interactions	B	+2%	$<1\%$	$<1\%$
Event Plane	B	4.8%	4.8%	4.8%
Fake Tracks	B	3.3%	3.3%	3.3%
E vs W	B	1.6%	3.6%	5.9%
AMPT correction	B	$\sim 0-3\%$	$\sim 0-3\%$	$\sim 0-3\%$
Total (approx.)	B	$^{+8\%}_{-7\%}$	$\pm 8\%$	$\pm 9\%$

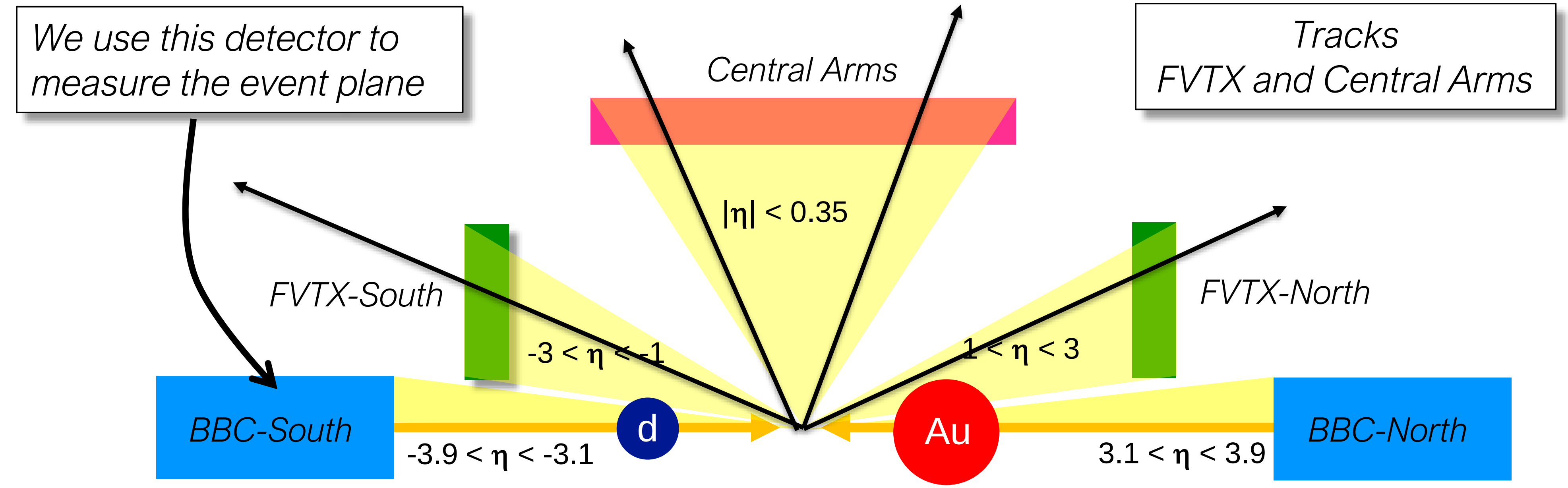
Cumulants: measure integrated v_2 from tracks in FVTX as a function of N_{trk}



- FVTX: forward vertex detector —silicon strip technology
- Very precise vertex/DCA determination
- No momentum determination, p_T dependent efficiency — measured v_2 roughly 18% higher than true

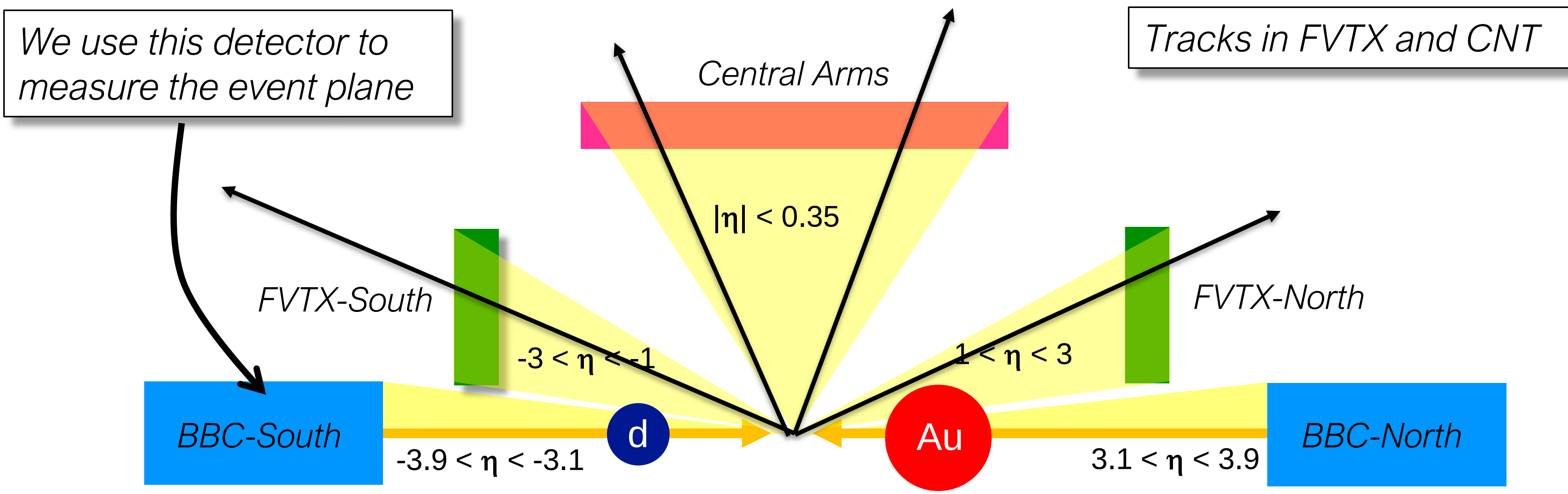


v_2 vs η: analysis method



- We want to measure integrated v_2 ($0<p_T<\infty$)
- No p_T information available from FVTX
- Devise a correction based on AMPT

v_2 vs η: analysis method



1. d+Au collisions generated with AMPT

- Determine parton-plane angle ,"true" ψ_2
- Use all final-state charged particles to determine "true" $v_2(\eta)$

2. reconstruct events with full GEANT simulation in PHENIX

- Analyze using final-state particles in the PHENIX acceptance to get $v_2(\eta)$

Correction factor = v_2 from step (2)/ (1)

- Apply correction to data $v_2(\eta)$
- Change the AMPT input parton cross section (and resulting v_2)→ repeat
- Change the input p_T spectra → repeat

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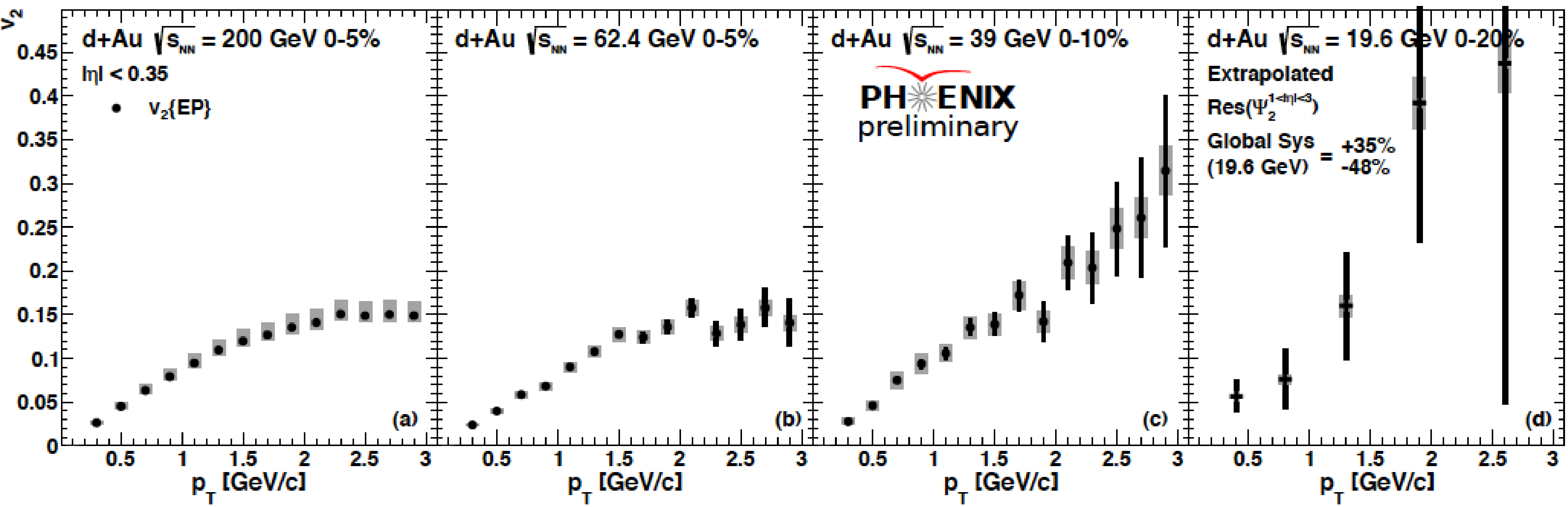
dAu BES: Event plane measurements of v_2

200 GeV **62 GeV** **39 GeV** **20 GeV**



Nearly identical

Increase at high p_T ?